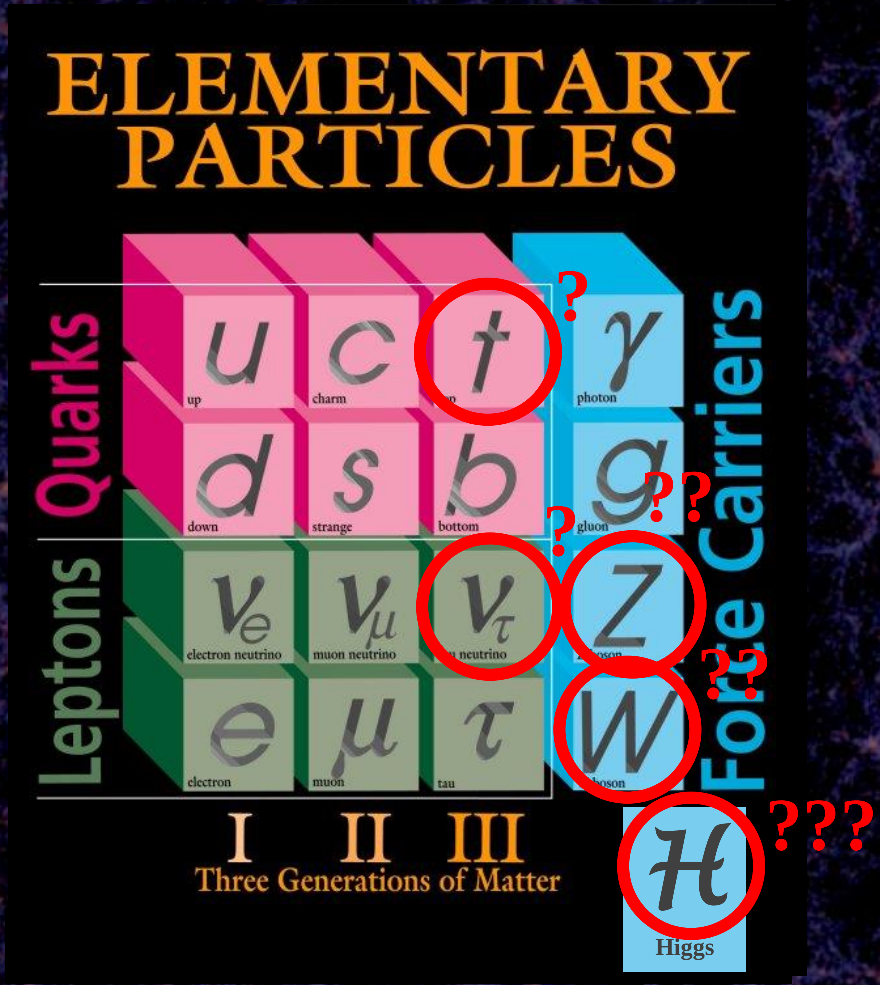
Neutrinos overview.

Dave Wark
Imperial IoP Meeting
April 8th, 2019

Advanced thanks to the many people I stole slides from, and apologies to those ignored as I will make no attempt to be complete.

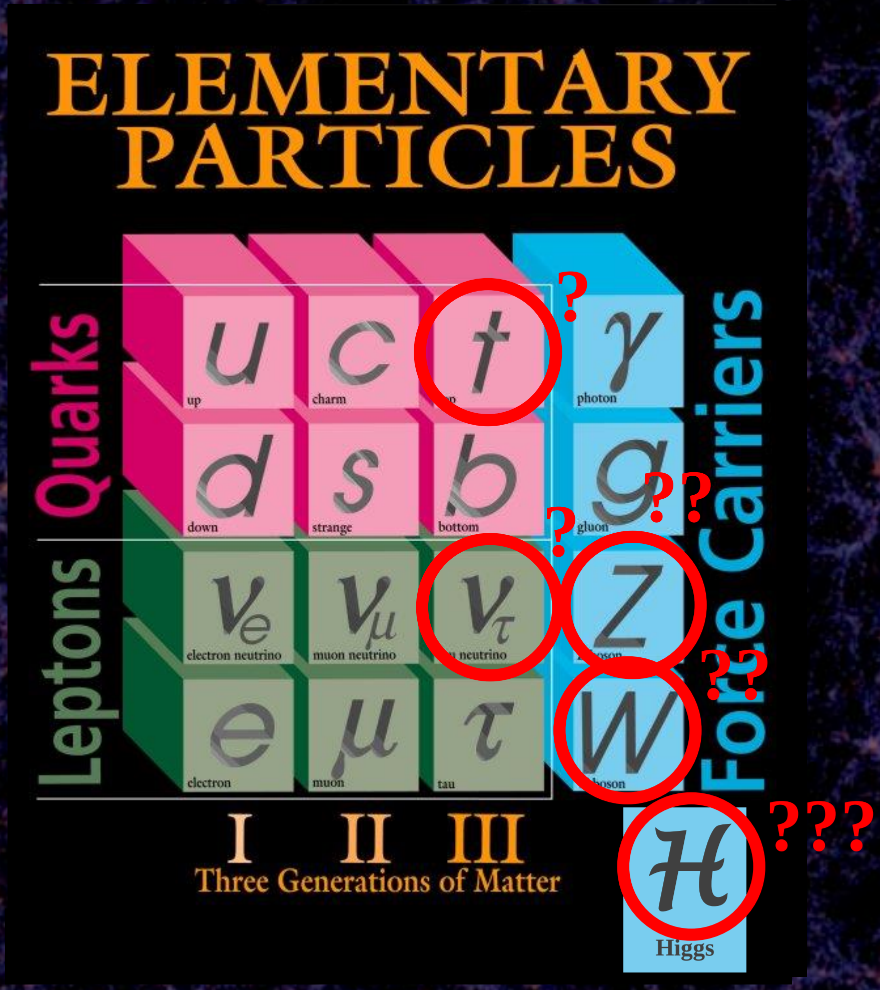
The Standard Model (~1981)

- Neutrinos in the 1981 Standard:
  - Three neutrinos with a conserved lepton flavour number.
  - Massless.
  - Strictly Left-handed.



The Standard Model (~now)

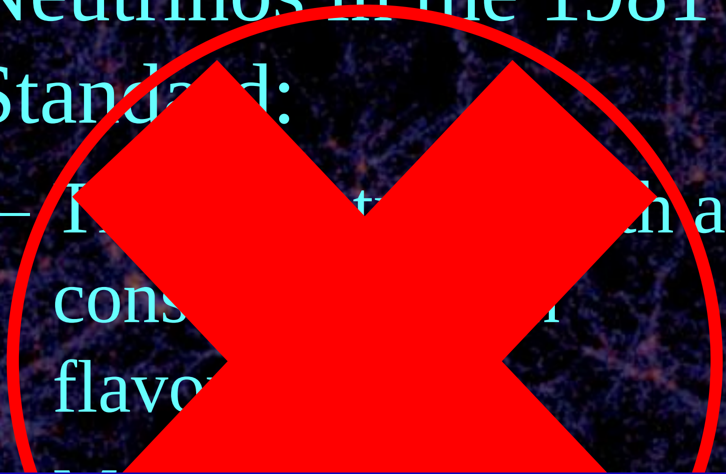
- Neutrinos in the 1981 Standa d:
  - T t h a cons flavo
  - M
  - Stri y Left-h ded.

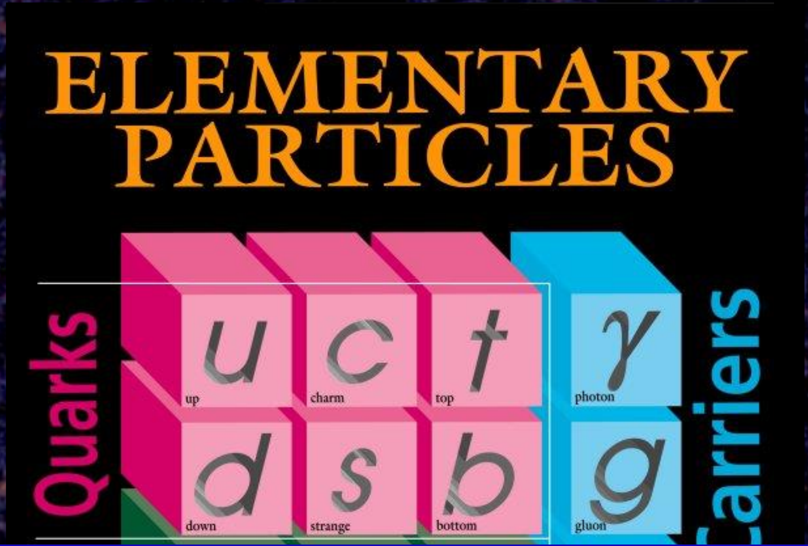


Dave Wark
Oxford U./RAL

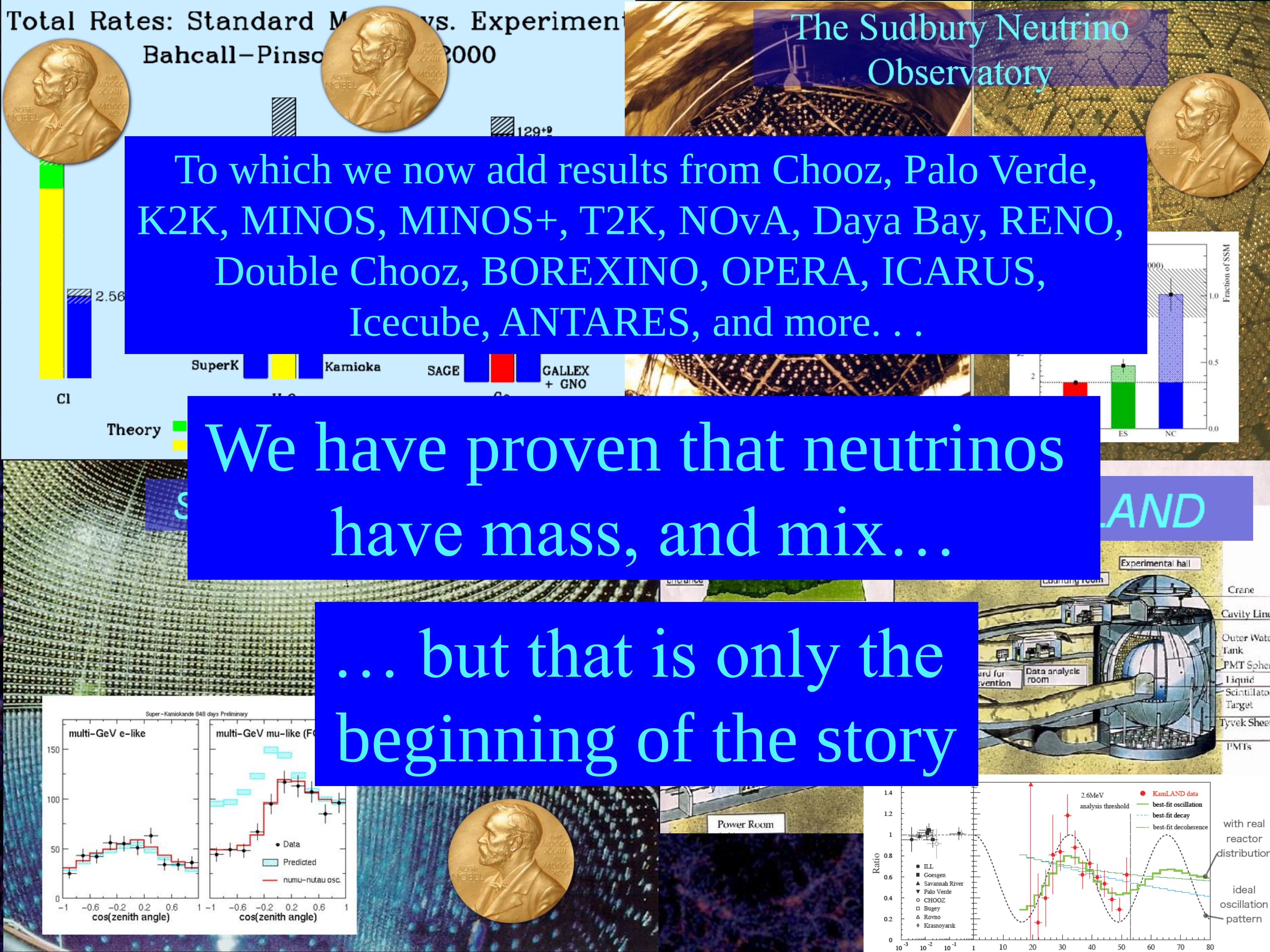
The Standard Model (~now)

- Neutrinos in the 1981 Stand d:
  - Th t h a
    cons
    flavo





- During my career, the neutrino side has been completely transformed.
- We cannot understand particle physics without understanding neutrinos, and we aren’t finished.
- We will not get this information from any other source, we must build more neutrino experiments.


To which we now add results from Chooz, Palo Verde, K2K, MINOS, MINOS+, T2K, NOvA, Daya Bay, RENO, Double Chooz, BOREXINO, OPERA, ICARUS, Icecube, ANTARES, and more. . .
We have proven that neutrinos have mass, and mix…
… but that is only the beginning of the story
Total Rates: Standard M vs. Experiment
Bahcall–Pinso 2000
The Sudbury Neutrino Observatory
SuperK
Kamioka
SAGE
GALLEX + GNO
Cl
Theory
2.56
ES
NC
Fraction of SSM
Experimental hall
Crane
Data analysis room
Power Room
Super-Kamiokande 848 days Preliminary
multi-GeV e-like
multi-GeV mu-like
cos(zenith angle)
Data
Predicted
numu-nutau osc.
KamLAND data
best-fit oscillation
best-fit decay
best-fit decoherence
2.6MeV analysis threshold
with real reactor distribution
ideal oscillation pattern
Ratio
ILL
Goesgen
Savannah River
Palo Verde
CHOOZ
Bugey
Rovno
Krasnoyarsk

Some Open Experimental Questions in Neutrino Physics

Completing the picture of neutrino oscillations.

- Parker, Nonnenmacher, Sedgwick, Pidcott, Kaboth, Vann

Neutrino masses and nature – Majorana or Dirac?

- Di Valentino, Kroupova, Nirkko, Taylor, Patrick

Are there sterile neutrinos?

- Di Valentino, Barker, Boschi, Blake, Van den Pontseele

Using neutrinos as probes.

- Katori, Malek

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

If only two neutrinos contribute:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$

Complicated equation means covariances and degeneracies!

CP sensitivity mainly because this term flips sign for ν and anti-ν

$$\ldots \frac{\Delta m^2_{31} L}{4E} \times \left(1 + \frac{2a}{\Delta m^2_{31}} (1 - 2S^2_{13})\right)$$

$$+8C^2_{13}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E}$$

$$-8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \sin\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E}$$

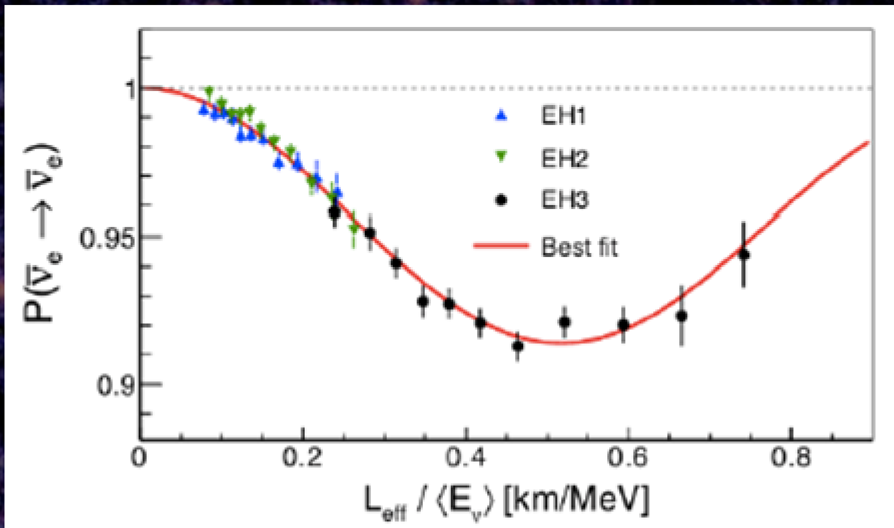
$$+4S^2_{12}C^2_{13}\{C^2_{12}C^2_{23} + S^2_{12}S^2_{23}S^2_{13} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\} \sin^2\frac{\Delta m^2_{21}L}{4E}$$

$$-8C^2_{13}S^2_{13}S^2_{23} \cos\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \frac{aL}{4E} (1 - 2S^2_{13})$$

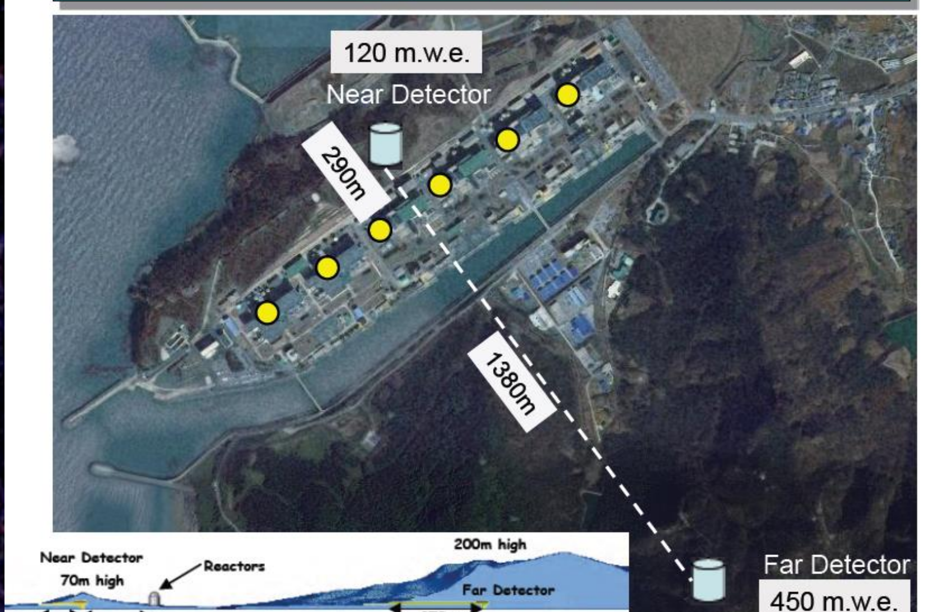
Need Matter effects to get the signs of Δm^2_{ij}

Is θ_{13} non-zero?

Neutrino Overview



RENO Experimental Set-up



The Double Chooz Experiment

Accelerator-Based Neutrino Oscillation Experients

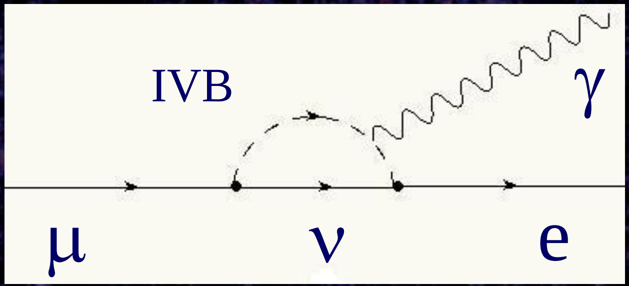
Dave Wark
Oxford U./RAL

More Ancient History…

- Question in the late 50's: Are the neutrinos in these reactions the same thing?:

$$n \rightarrow p + e + \nu \qquad \pi \rightarrow \mu + \nu \qquad \mu \rightarrow e + \nu + \nu$$

- If so, why no $\mu \rightarrow e + \gamma$ via diagrams like?:



Today this would be interpreted as a neutrino oscillation experiment, and in a different world that could have confused things greatly!

VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

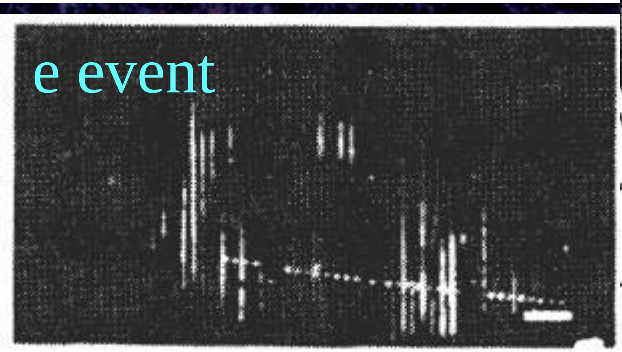


FIG. 1. Plan view of AGS neutrino experiment.

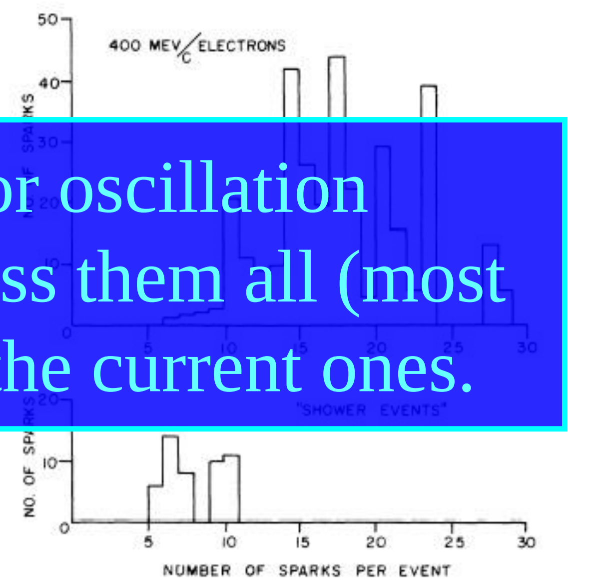
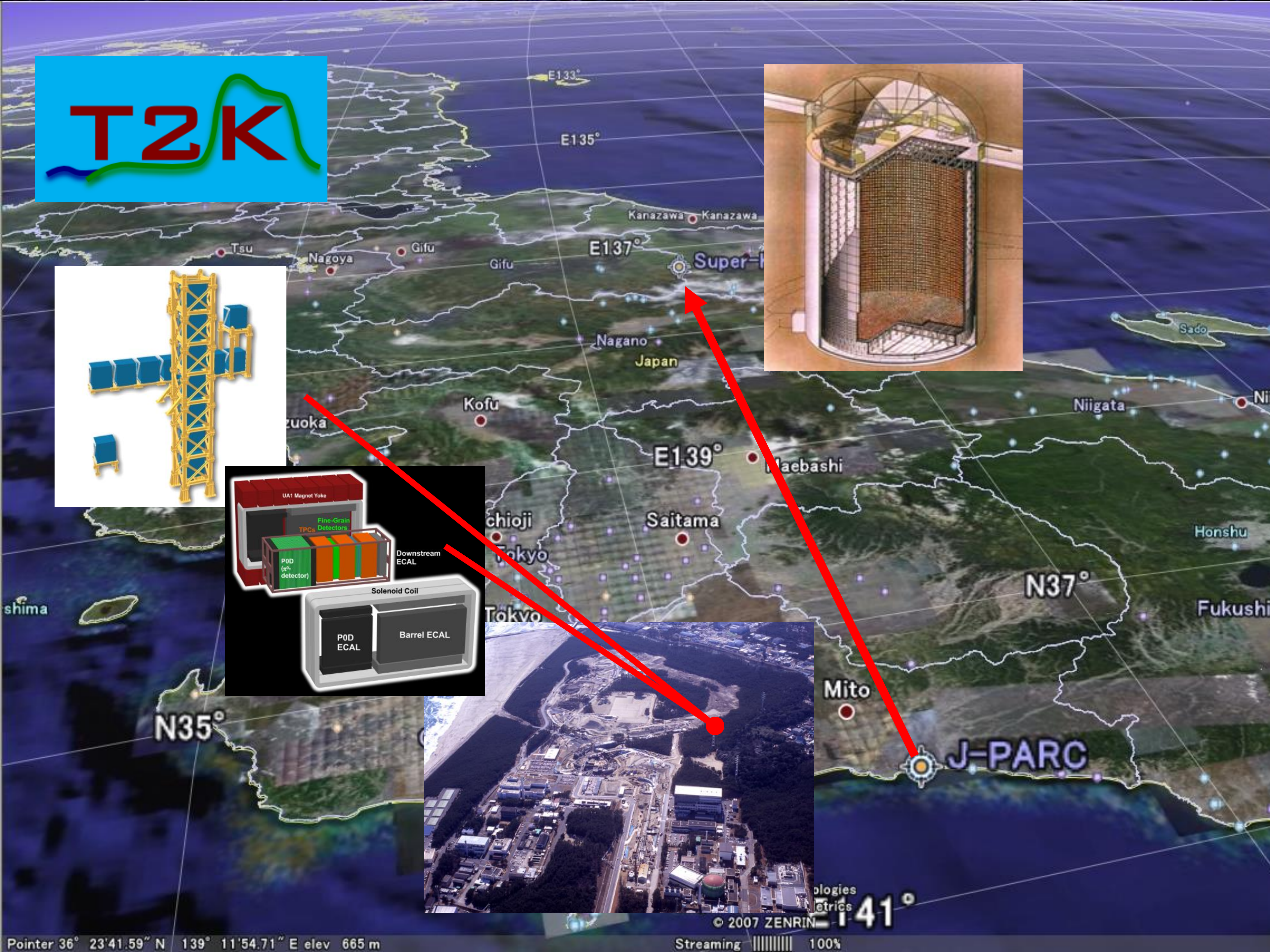


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

Fore-runner of accelerator oscillation experiments, no time to discuss them all (most notably MINOS) – jump to the current ones.


T2K
E133°
E135°
Kanazawa
Kanazawa
E137°
Tsu
Nagoya
Gifu
Gifu
Nagano
Japan
Sado
Niigata
Kofu
E139°
Saitama
Honshu
N37°
Mito
J-PARC
N35°
UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

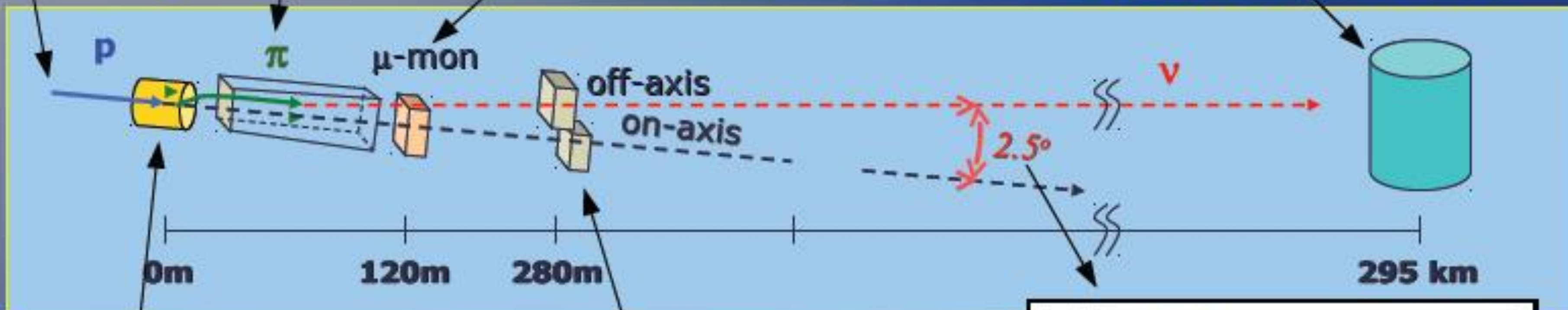
T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux

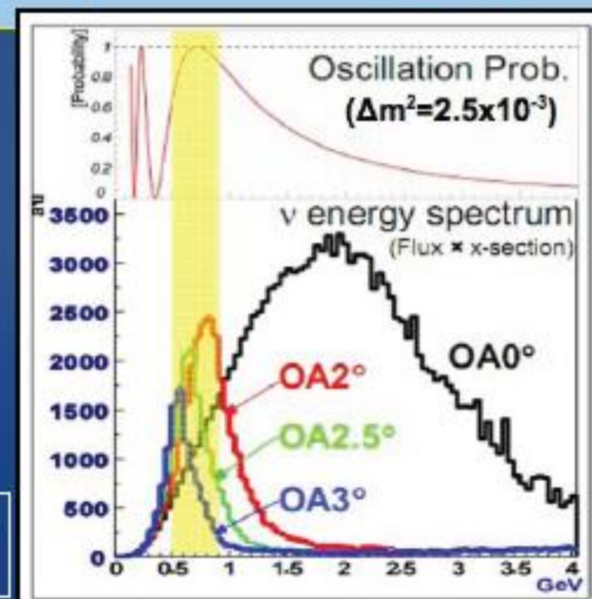


Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

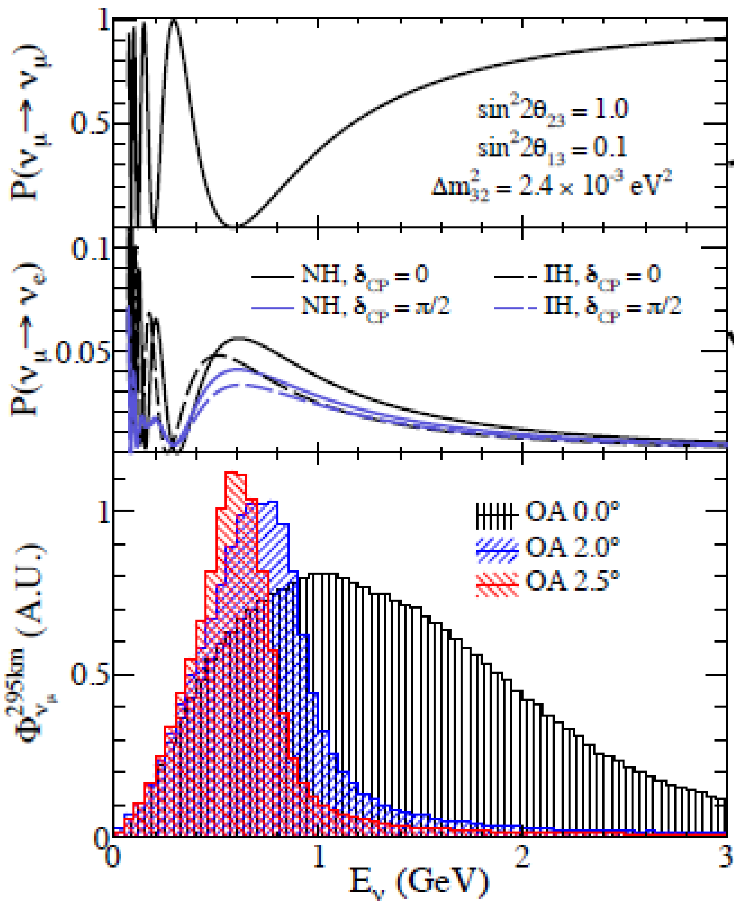
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

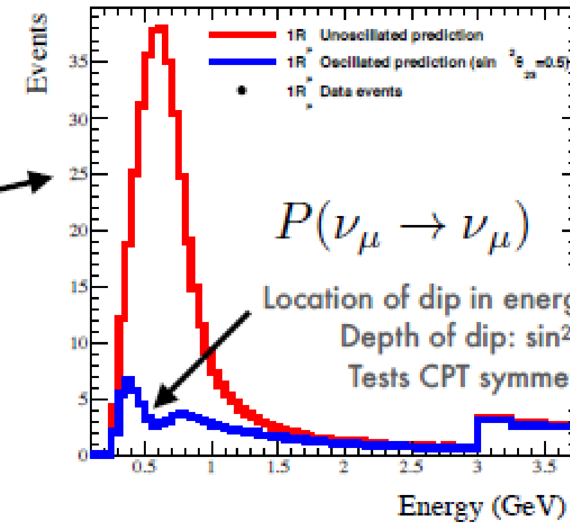
Off-axis ND280 detector measures spectra for various neutrino interactions



Beam peaked at 1st max E≈600 MeV

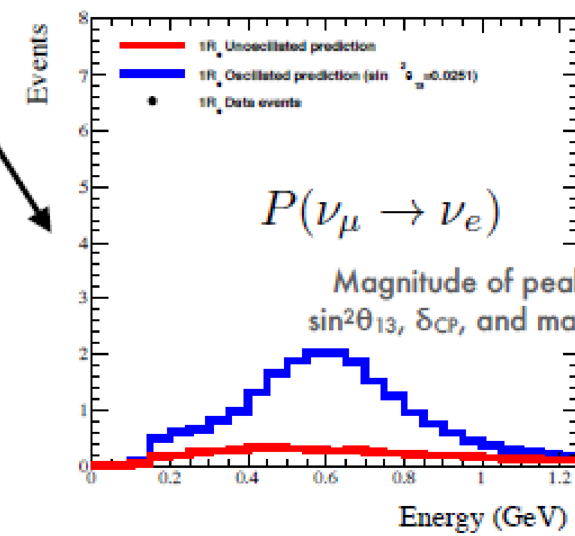
Long Baseline Neutrino Oscillation





$P(\nu_\mu \to \nu_\mu)$

Location of dip in energy: Δm^2_{32}
Depth of dip: $\sin^2\theta_{23}$
Tests CPT symmetry

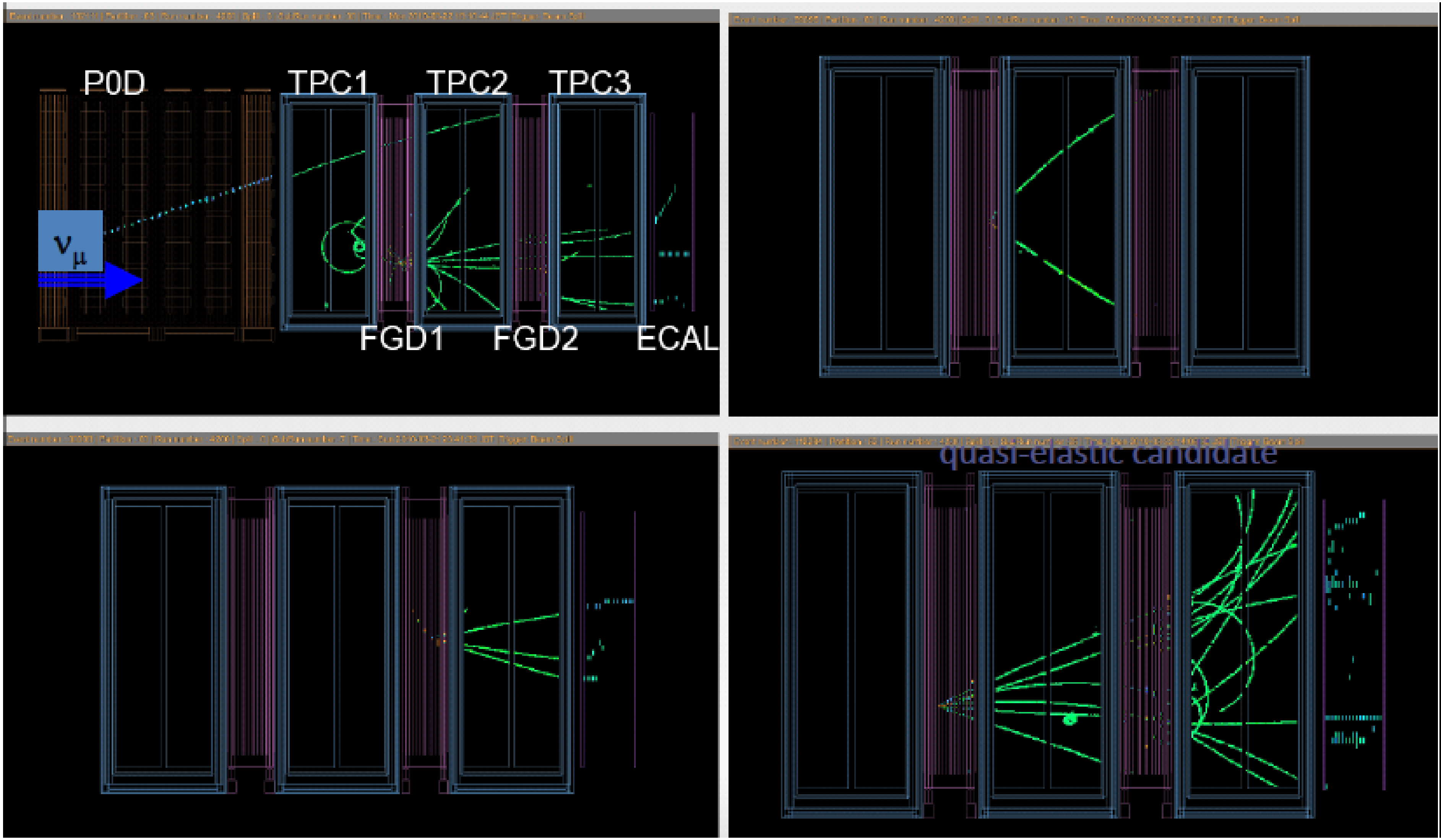


$P(\nu_\mu \to \nu_e)$

Magnitude of peak linked to
$\sin^2\theta_{13}$, δ_{CP}, and mass hierarchy

A few ND280 neutrino interaction candidates

CCQE candidate

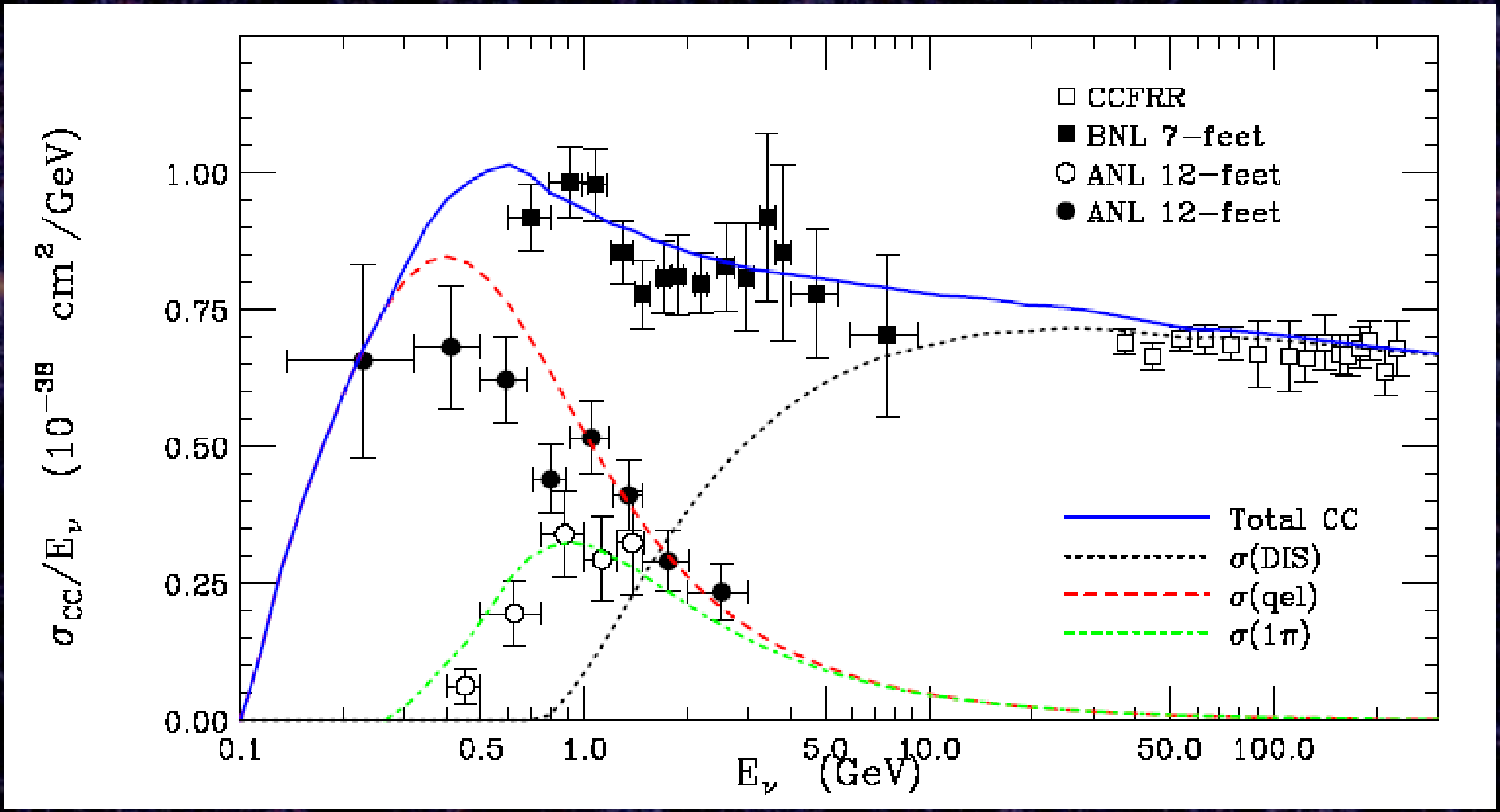


single pion candidate

DIS candidate

Critical σ's poorly known in range 0.1-10 GeV.

Total ν_μ CC cross section

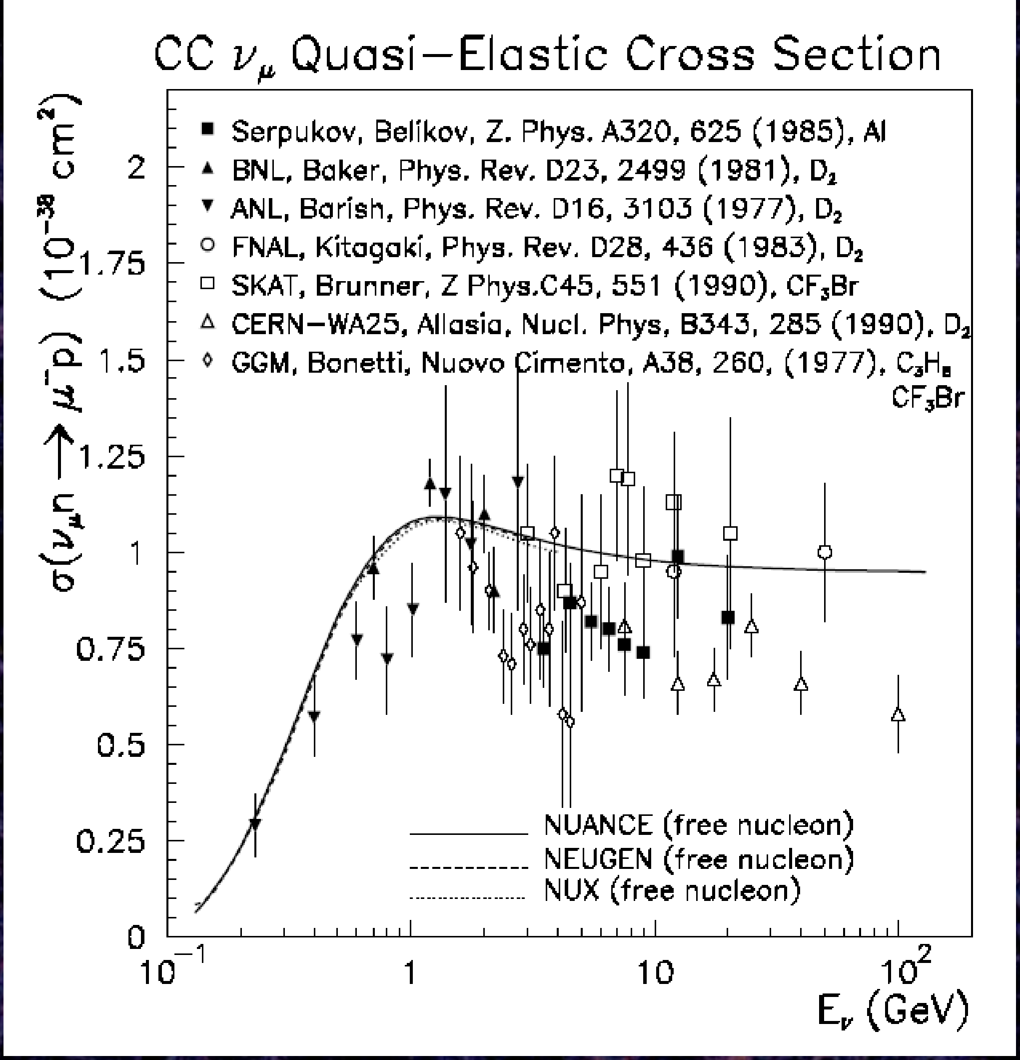


Data compiled by G.Zeller, hep-ex/0312061

Dave Wark
Oxford U./RAL

Cross sections are poorly known in range 0.1-10 GeV

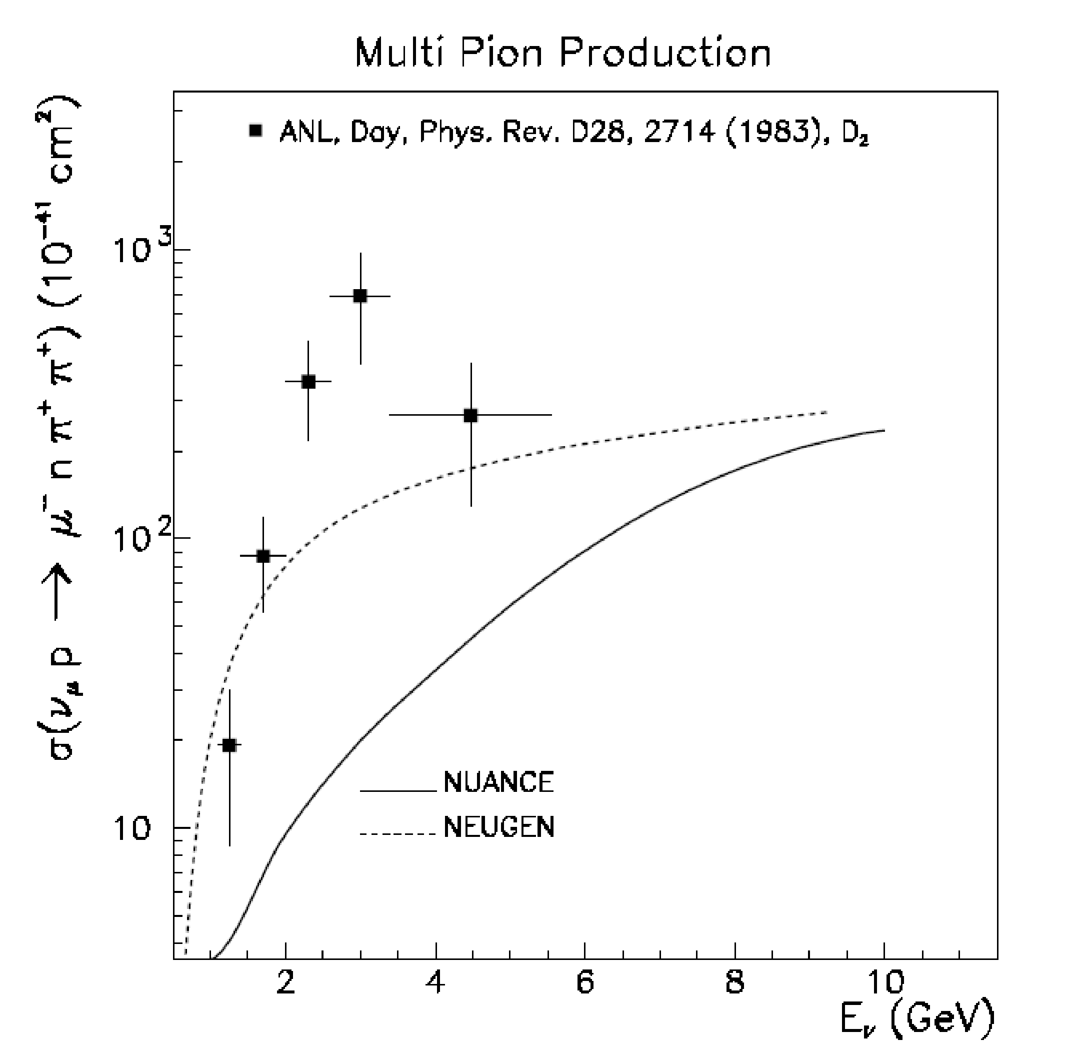
Data compiled by G.Zeller, hep-ex/0312061



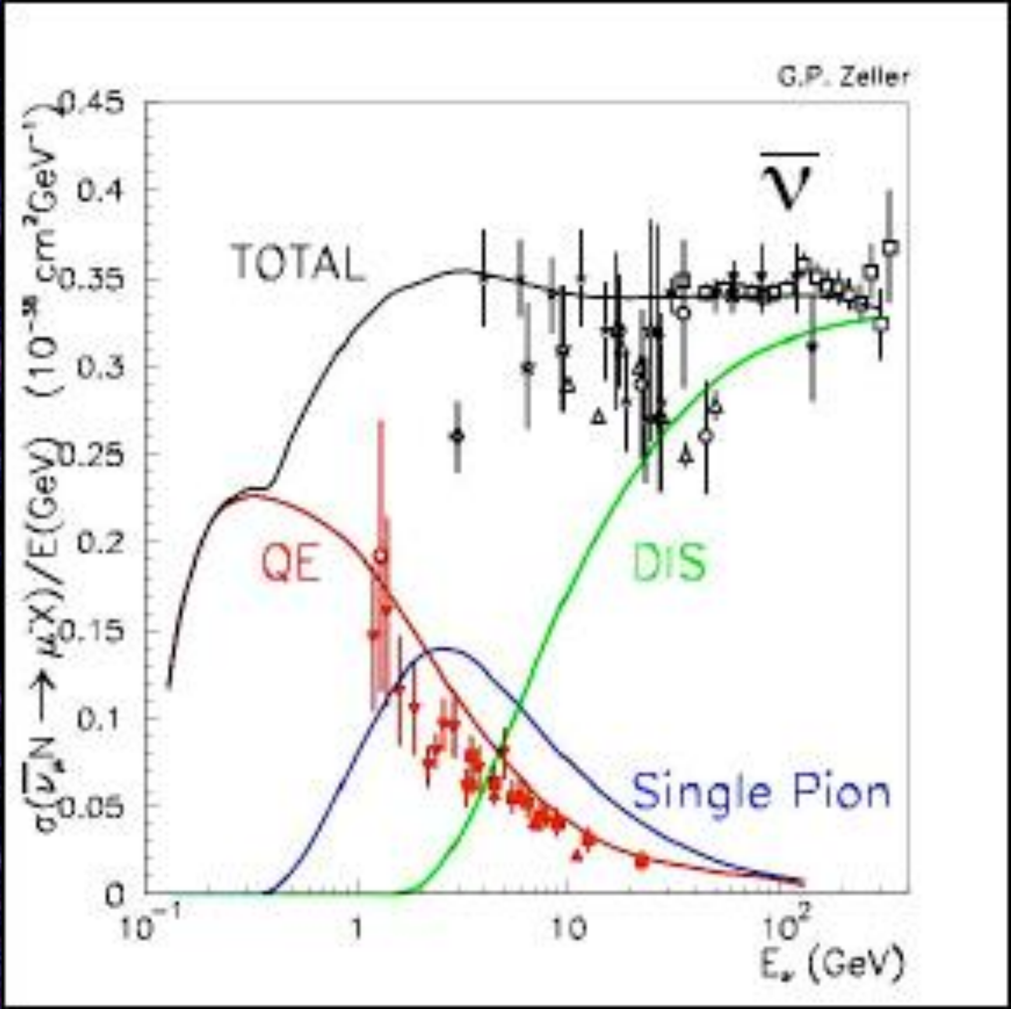
Dave Wark
Oxford U./RAL

Cross sections are poorly known in range 0.1-10 GeV

Data compiled by G.Zeller, hep-ex/0312061



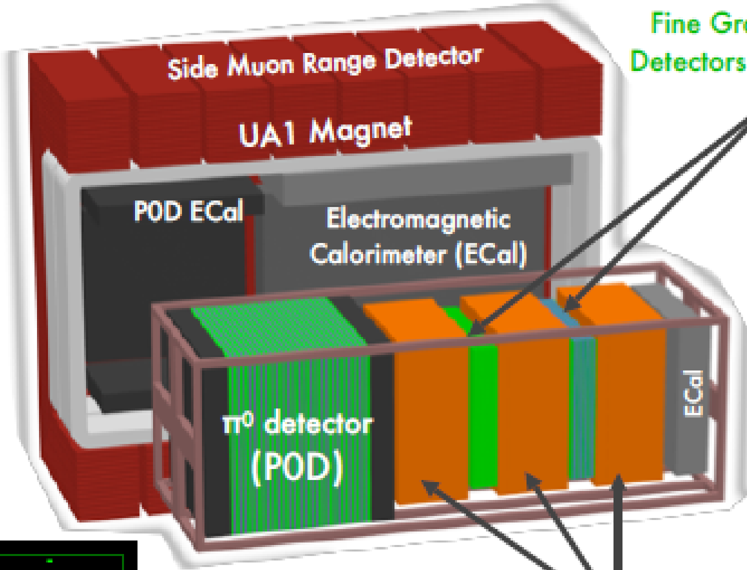
And lets not even talk about $\bar{\nu}$…



T2K Off-Axis Near Detector

Beam →

Primary Interaction Materials:
Carbon, Oxygen
Secondary Interaction Materials:
Hydrogen, Lead, Brass, Argon



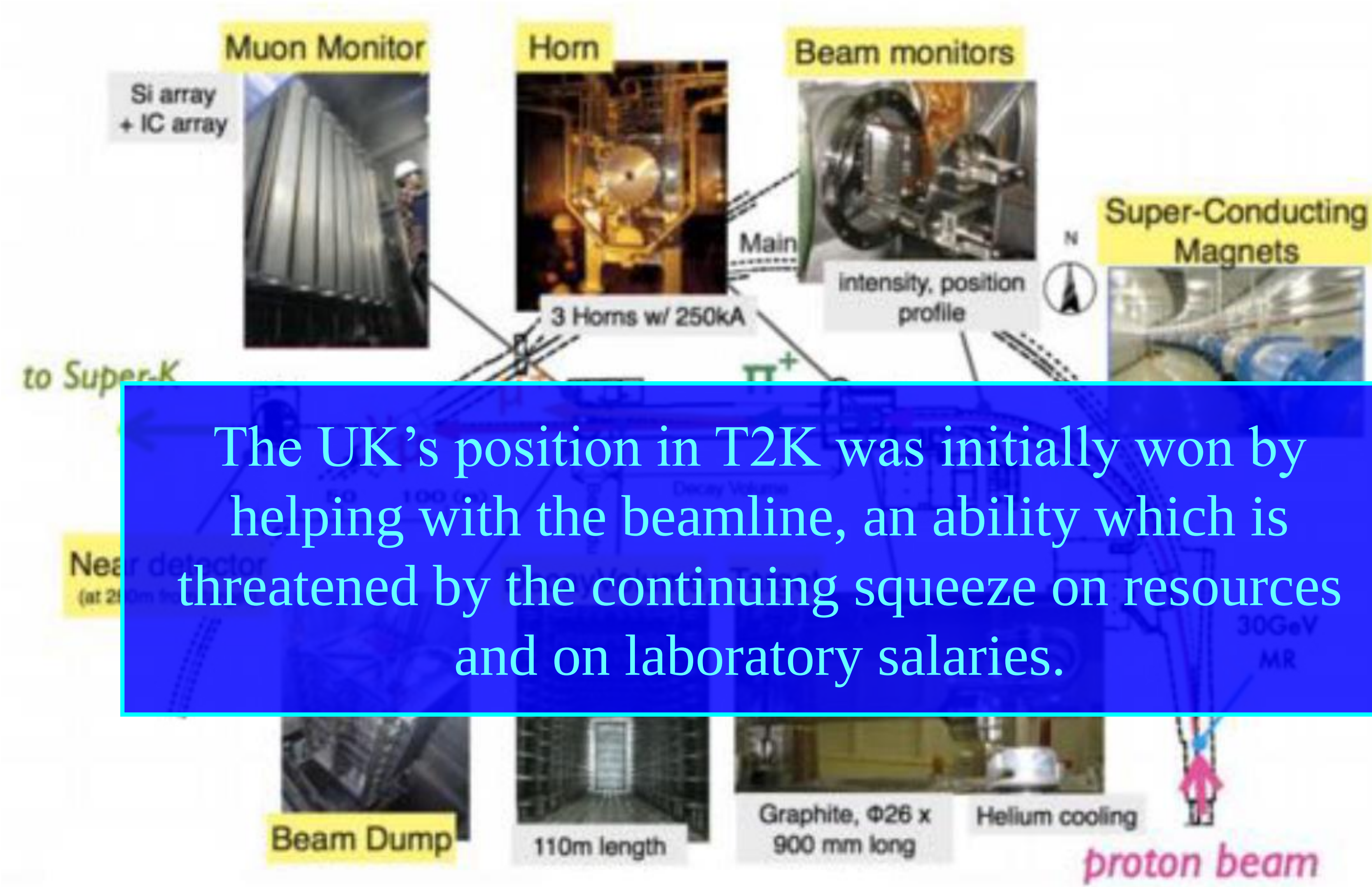
Interaction in P0D

Interaction in FGD1

Interaction in ECal

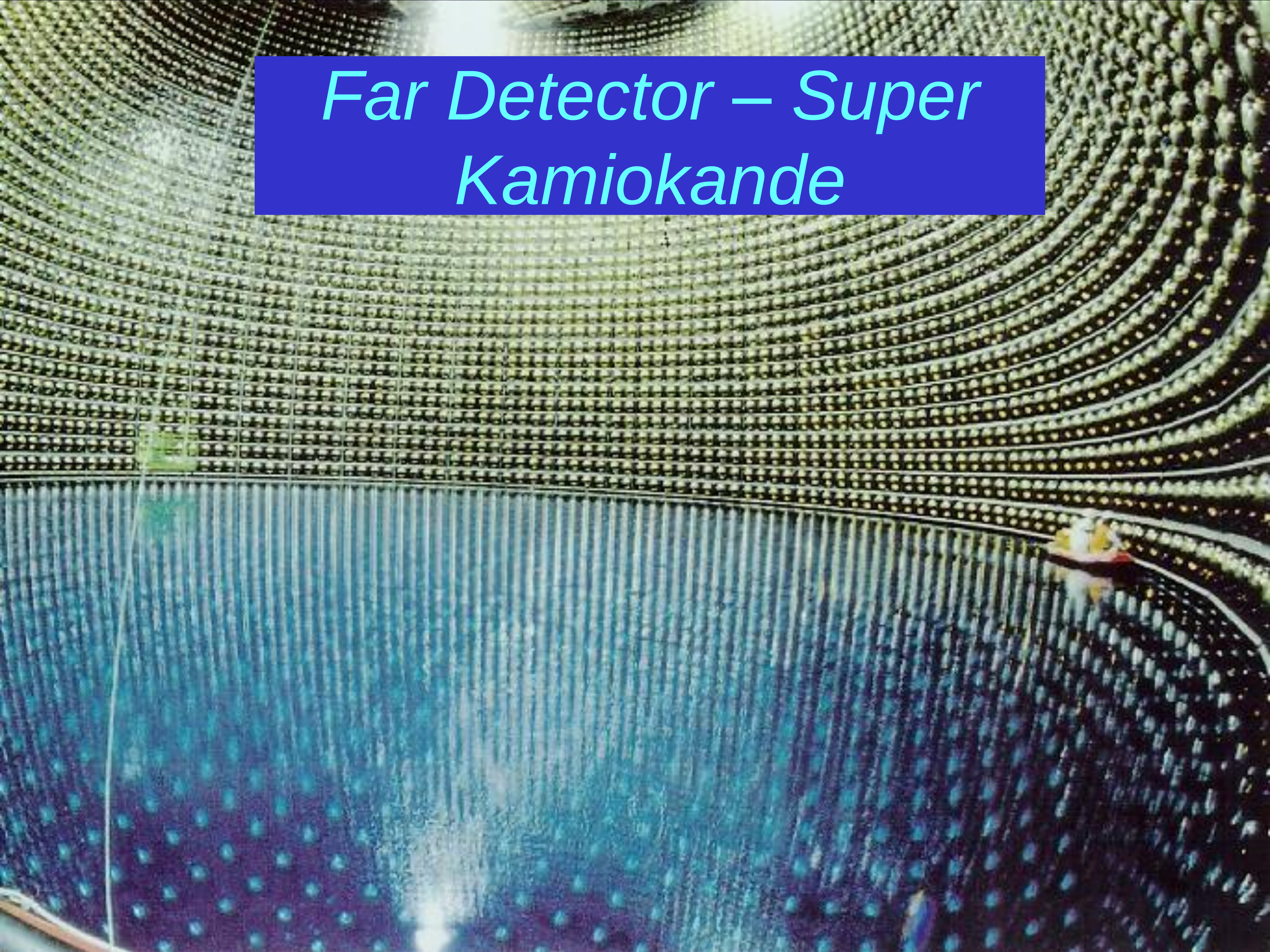
See the talk by HEPP Prize winner Asher Kaboth, who will tell you everything you need to know about near detectors!

J-PARC Neutrino Beamline

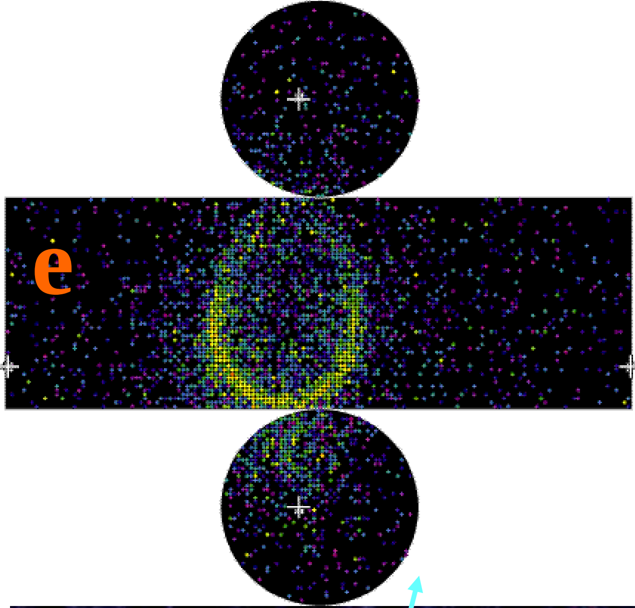


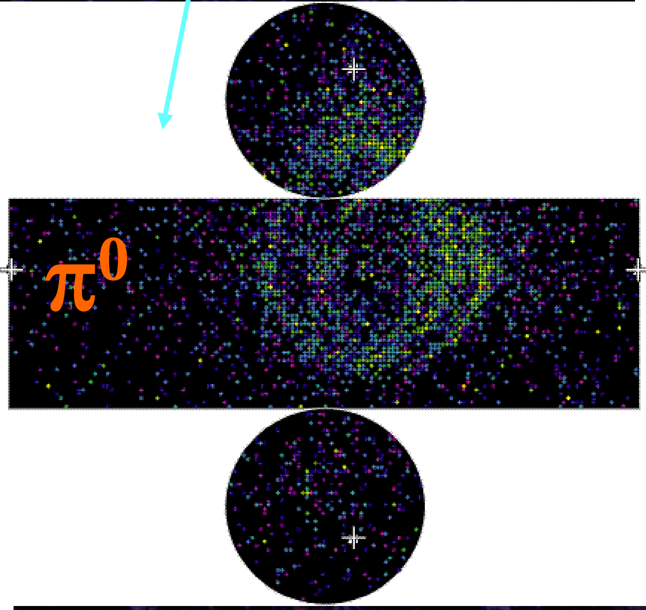
The UK's position in T2K was initially won by helping with the beamline, an ability which is threatened by the continuing squeeze on resources and on laboratory salaries.

Far Detector – Super Kamiokande



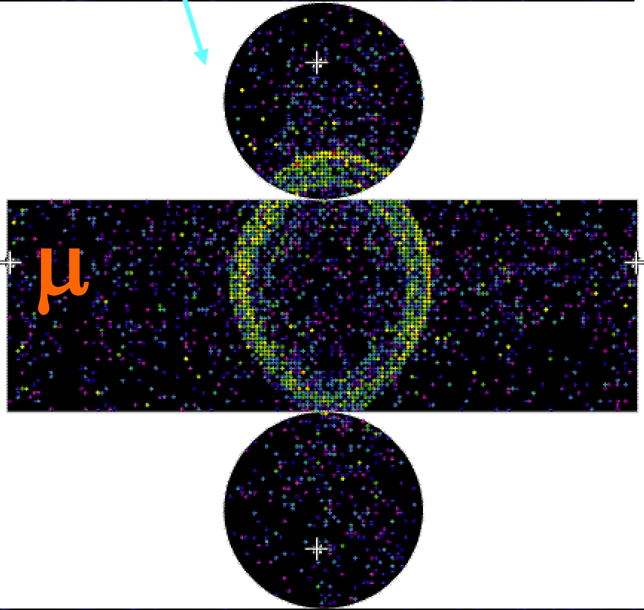
Background from NC interactions





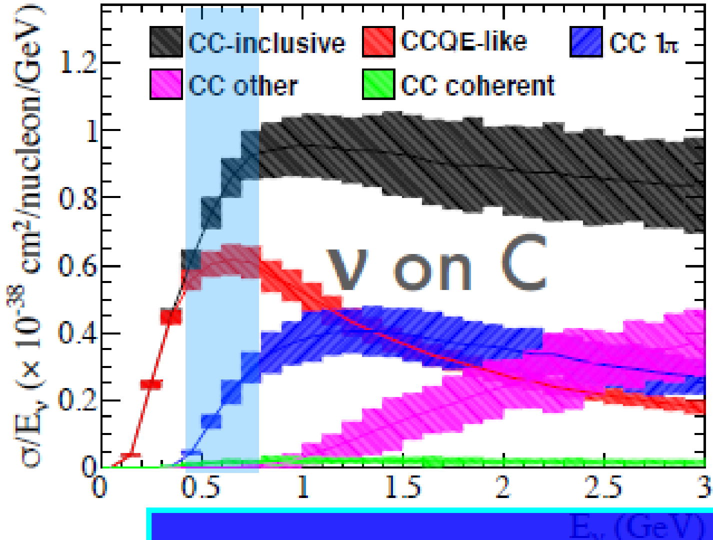
ν_μ disappearance signal

ν_e appearance signal

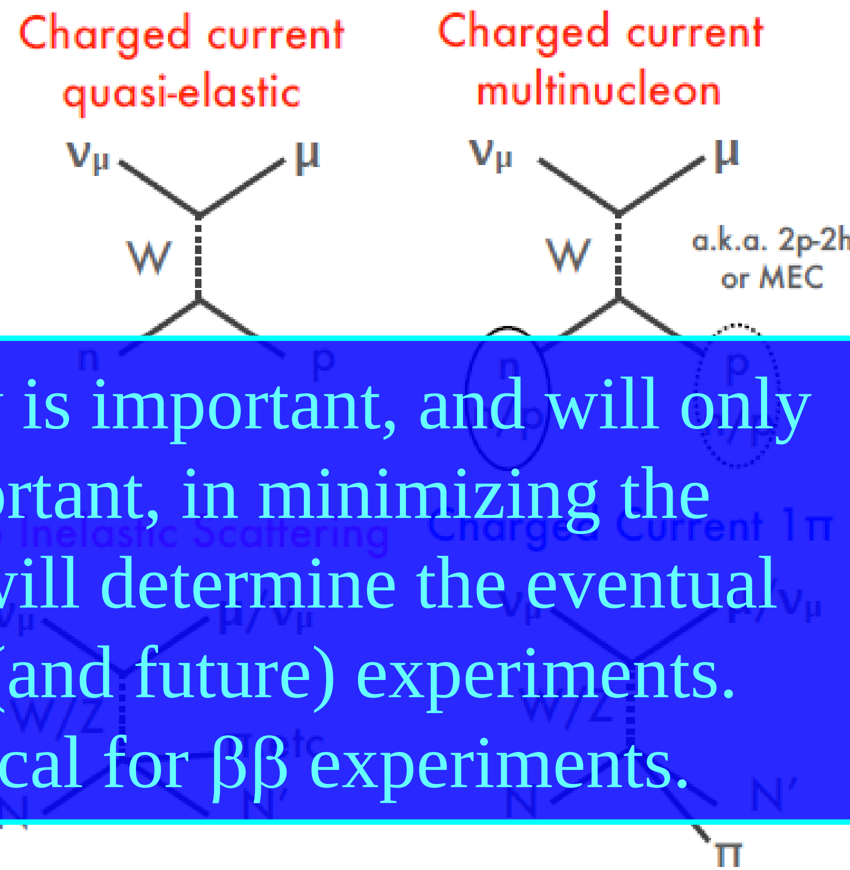


In this energy range, Super Kamiokande well understood, Excellent for separating electrons, μ, π^0

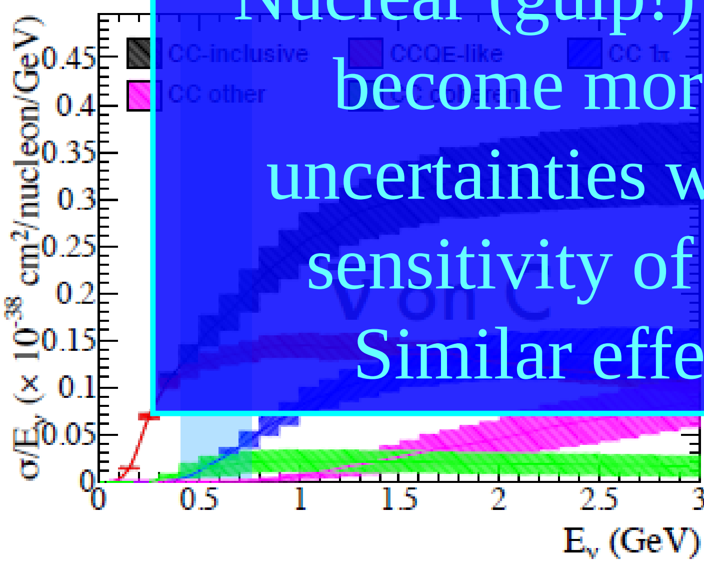
ν-N Cross Section Model



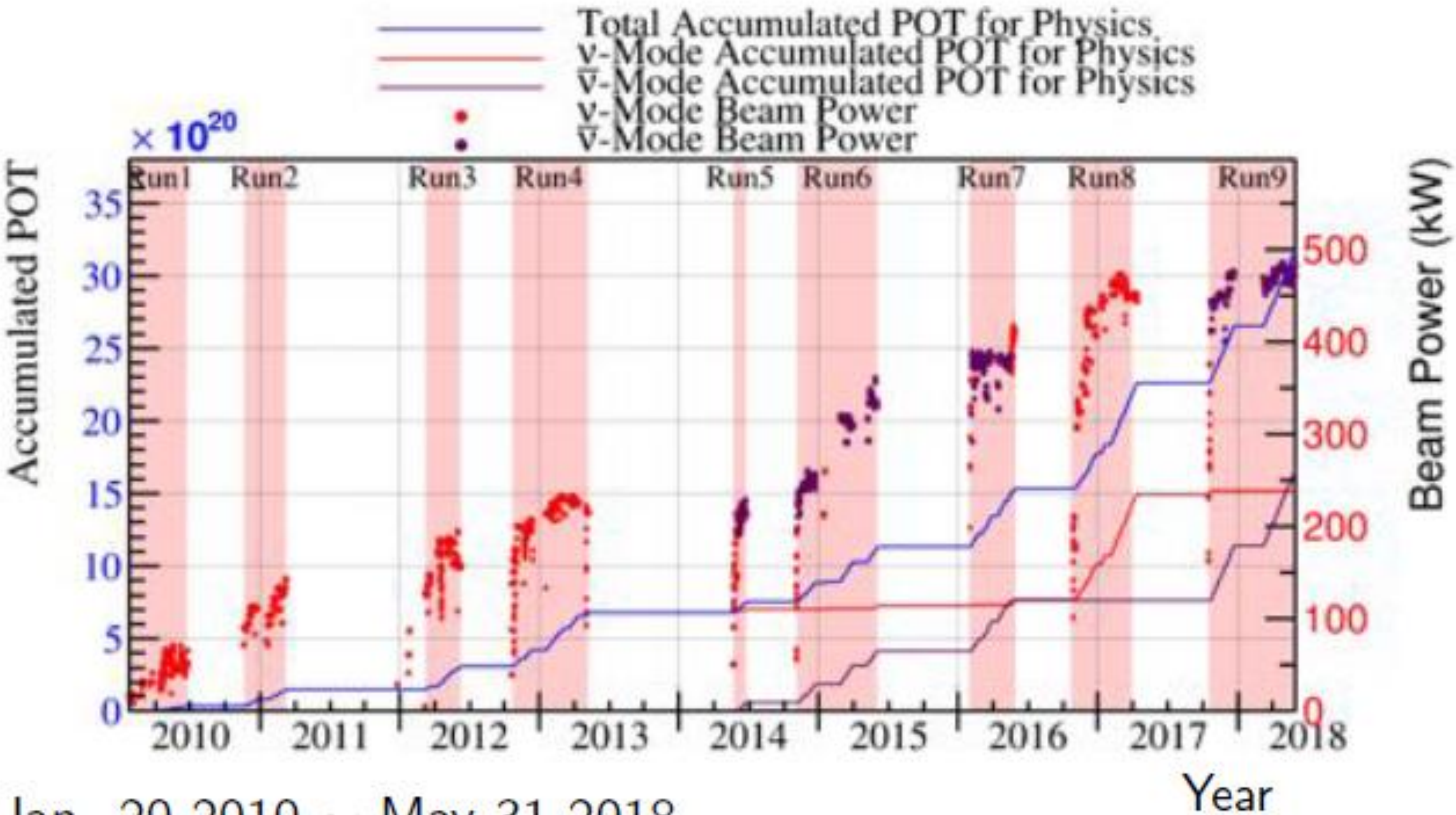
Uncertainties come from underlying model parameters and normalizations



Nuclear (gulp!) theory is important, and will only become more important, in minimizing the uncertainties which will determine the eventual sensitivity of these (and future) experiments. Similar effect critical for ββ experiments.

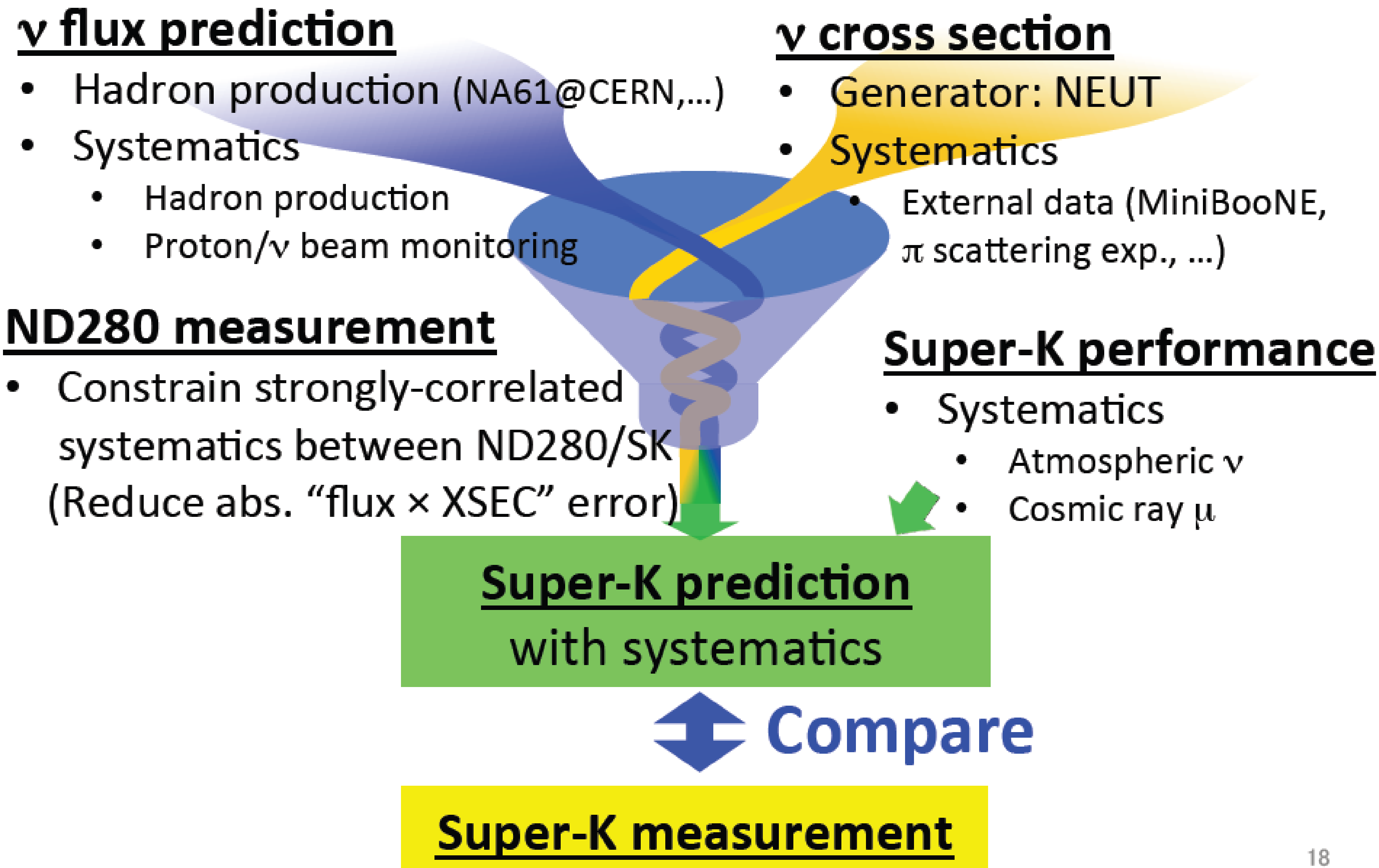


T2K Data-Taking Status



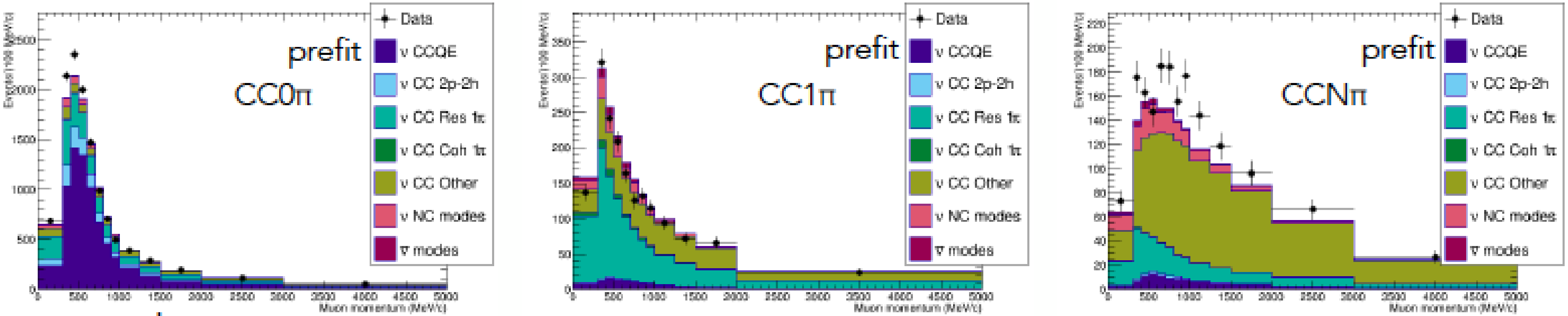
- Jan. 20 2010 ∼ May 31 2018
- 3.16×10^{21} Protons On Target (POT) accumulated so far
  - 1.51×10^{21} POT ν-Mode + 1.65×10^{21} POT $\bar{\nu}$-Mode
- Latest oscillation results based on :
  - $3.13 \times 10^{21} = \sim 1.49 \times 10^{21}\ \nu + \sim 1.63 \times 10^{21}\ \bar{\nu}$ POT
  - 40% of the total approved T2K statistics (7.8×10^{21} POT)

Neutrino oscillation analysis principle



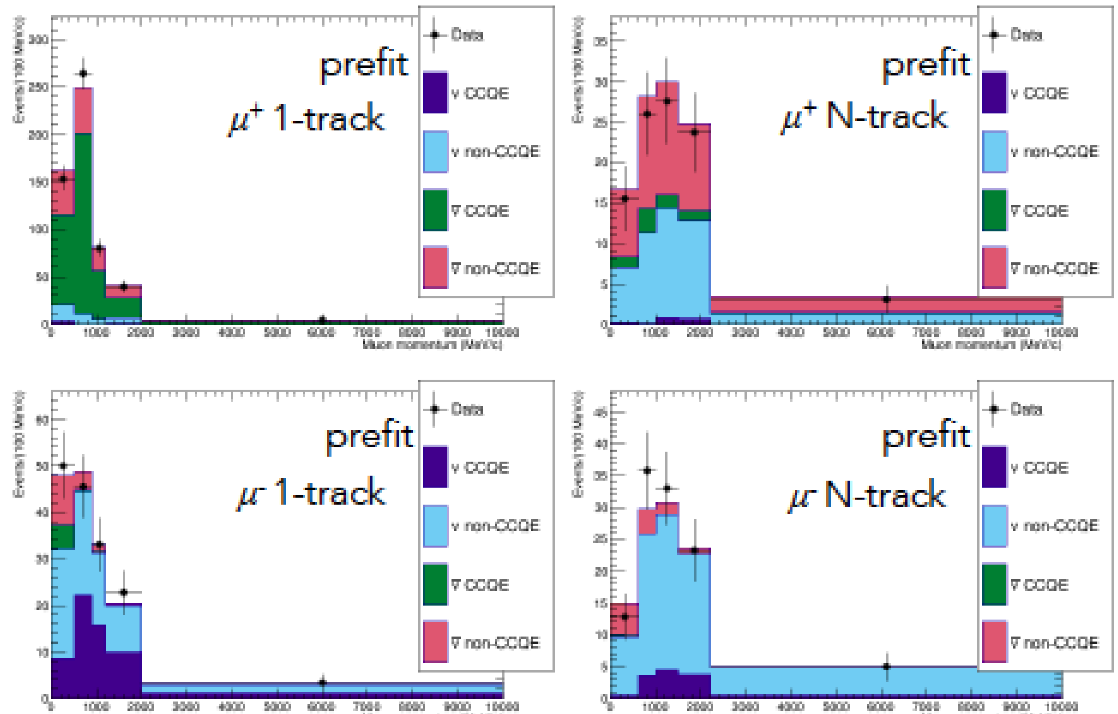
NEAR DETECTOR SAMPLES

P1.036 C. Riccio



ν-mode

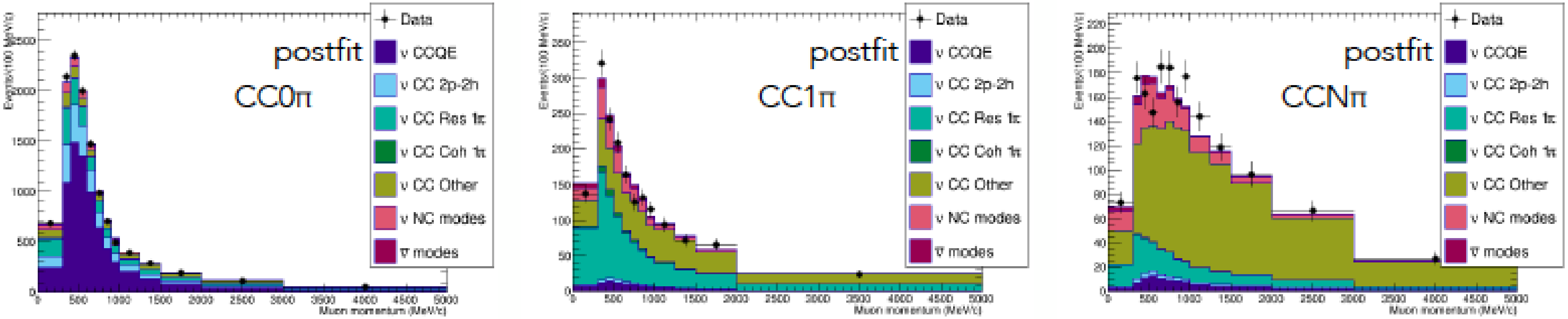
$\bar{\nu}$-mode



- 6 ν-mode samples (FGD1,2) 5.8×10^{20} POT
  - ν_μ CC0π, CC1π, CCnπ
- 8 $\bar{\nu}$-mode samples (FGD1,2) 2.8×10^{20} POT
  - $\bar{\nu}_\mu$ CC 1-track, CC N-track + ν_μ "wrong sign"
- simultaneous fit of μ momentum/angle:
  - FGD1 (all plastic) and FGD2 (water+plastic)
  - Flux parameters increase by ~15%
  - Cross sections ~consistent with input
- P-value = 8.6%
- Reduce uncertainties from 12-15% to 5-8%

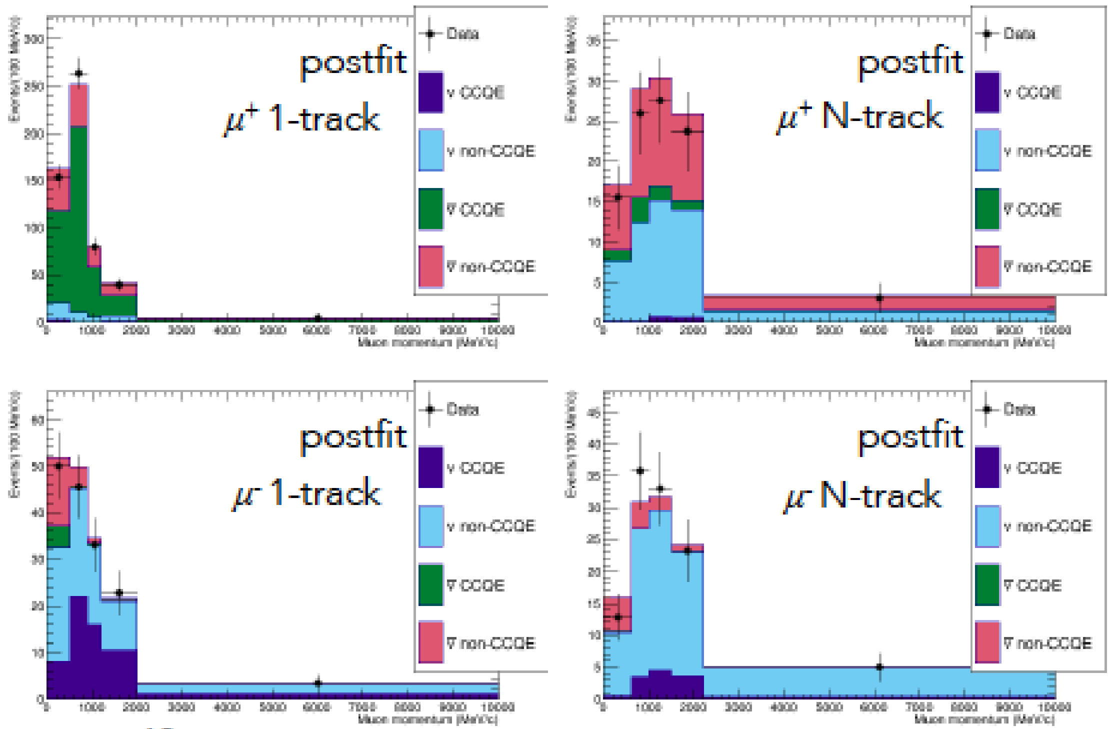
NEAR DETECTOR SAMPLES

P1.036 C. Riccio



ν-mode

$\bar{\nu}$-mode



- 6 ν-mode samples (FGD1,2) 5.8x10^{20} POT
  - ν_μ CC0π, CC1π, CCnπ
- 8 ν-mode samples (FGD1,2) 2.8x10^{20} POT
  - $\bar{\nu}_\mu$ CC 1-track, CC N-track + ν_μ “wrong sign”
- simultaneous fit of μ momentum/angle:
  - FGD1 (all plastic) and FGD2 (water+plastic)
  - Flux parameters increase by ~15%
  - Cross sections ~consistent with input
- P-value = 8.6%
- Reduce uncertainties from 12-15% to 5-8%

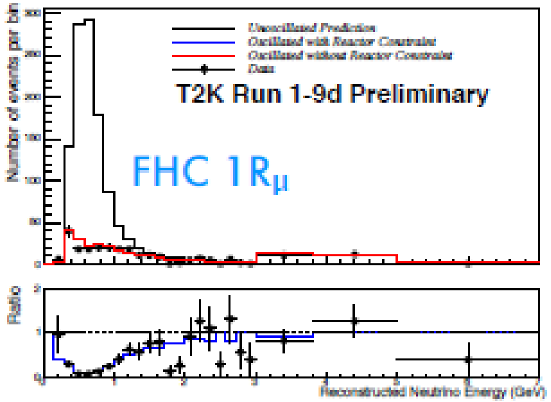
FHC = ν-mode
RHC = $\bar{\nu}$-mode
1 d.e. = CC1π sample

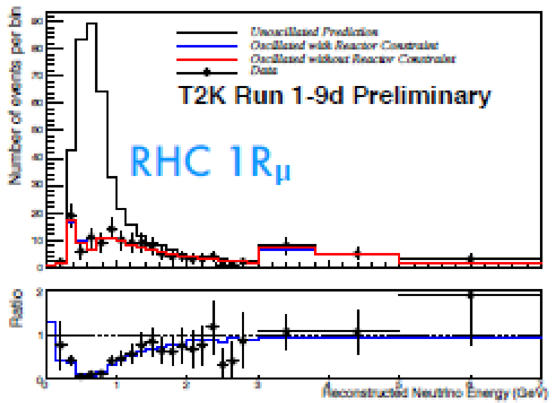
T2K Systematics

% Errors on Predicted Event Rates

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09	2.67
E_b	2.38	1.72	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Osc	0.03	0.03	2.69	2.49	2.63	0.77
All Systematics	5.12	4.45	8.81	7.13	18.38	5.96
All with osc	5.12	4.45	9.19	7.57	18.51	6.03

With these uncertainties would become systematics limited with ~300 appearance events.

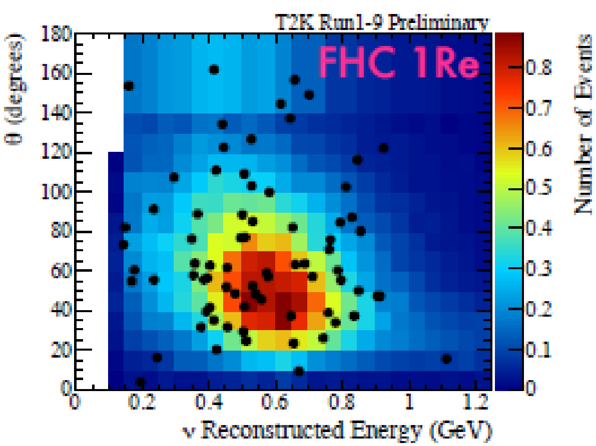


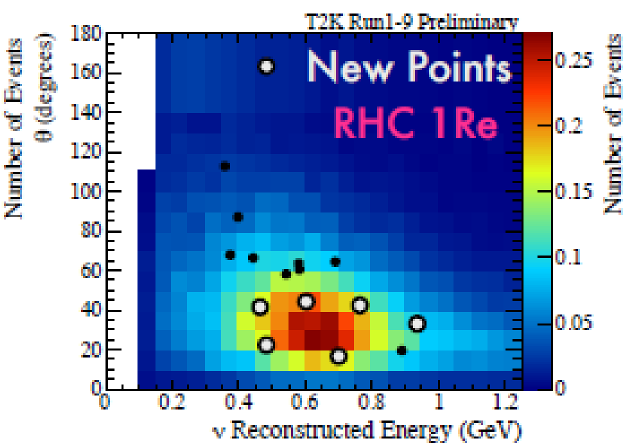


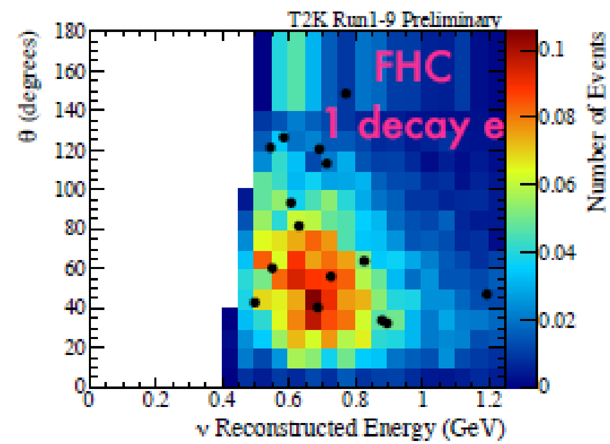
SK Data

Predictions with: $\sin^2\theta_{13}=0.0212$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.51\times10^{-3}$, NH

Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
FHC 1R$_\mu$	272.4	272.0	272.4	272.8	243
RHC 1R$_\mu$	139.5	139.2	139.5	139.9	140
FHC 1Re	74.4	62.2	50.6	62.7	75
RHC 1R$_e$	17.1	19.4	21.7	19.3	15
FHC 1 decay e	7.0	6.1	4.9	5.9	15

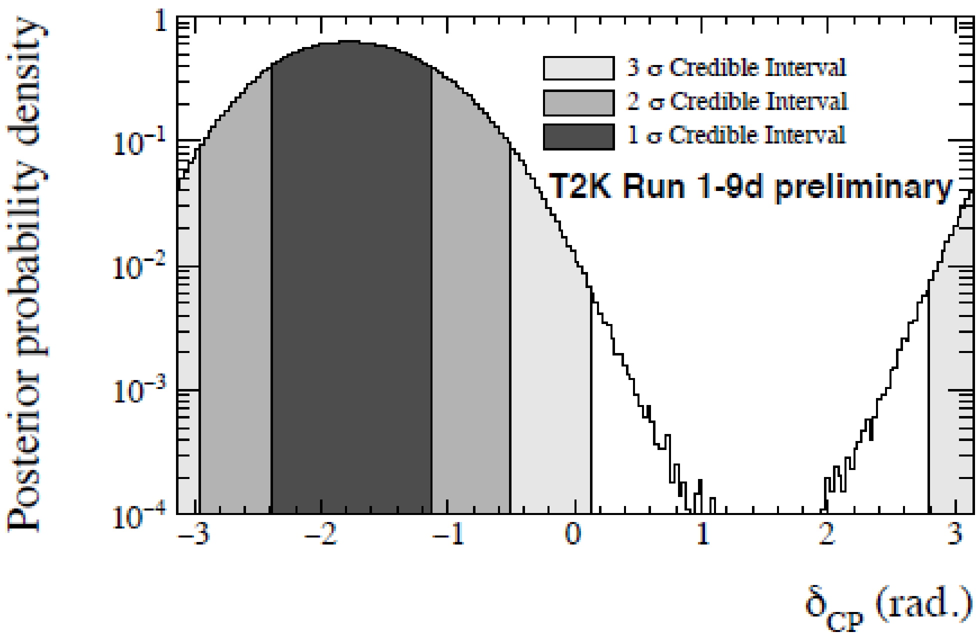


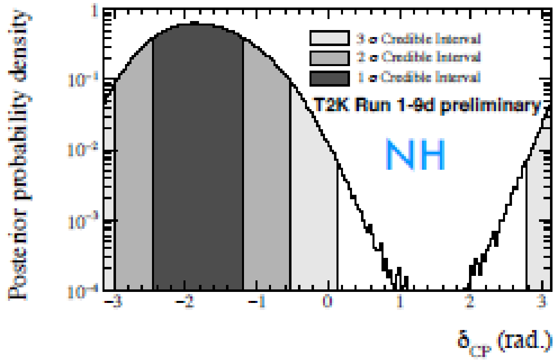


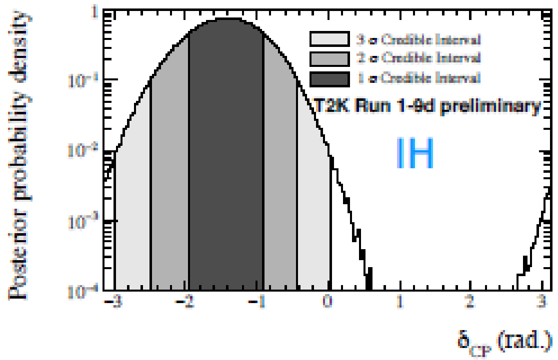


CP Violation

Results shown are for with reactor constraint; T2K only in back up



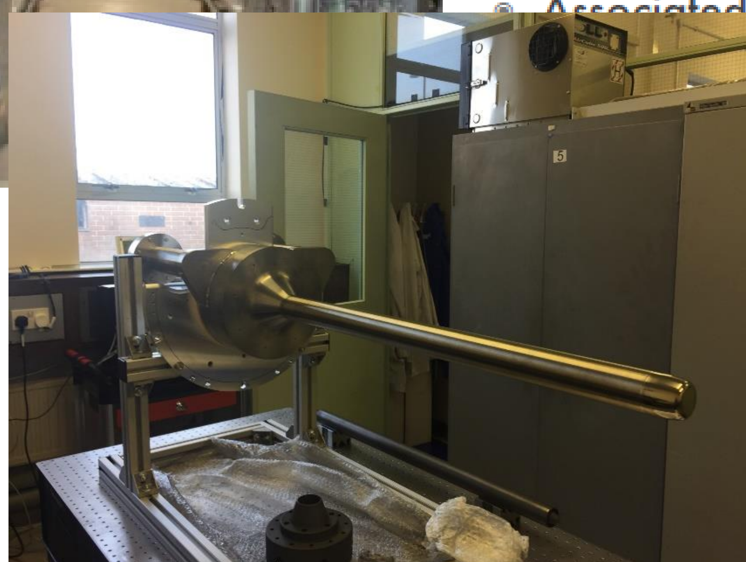


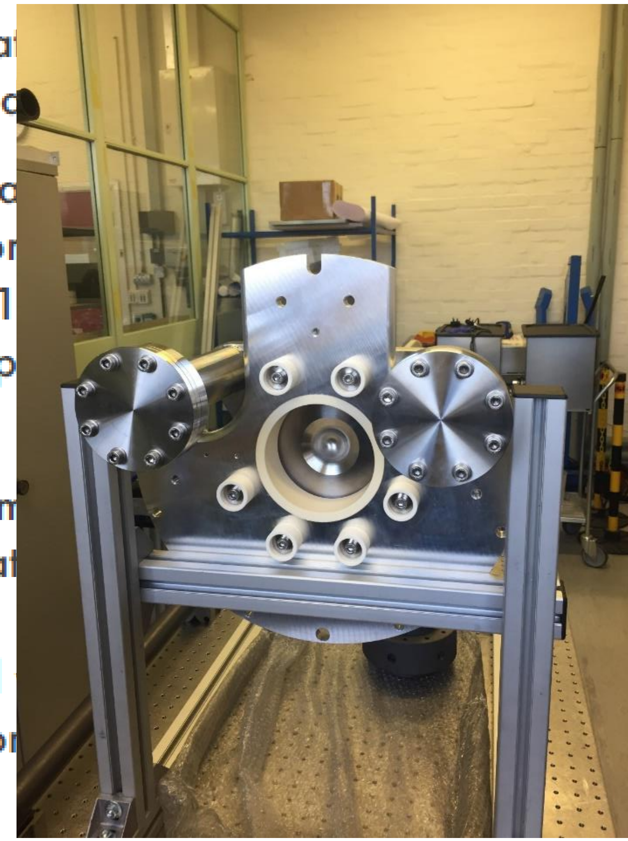


- T2K excludes CP conservation at 2σ but not 3σ
- Best fit value, marginalized over hierarchy, is δ_{CP}=-1.74
- T2K result is still stronger than expected sensitivity

Beam Upgrade

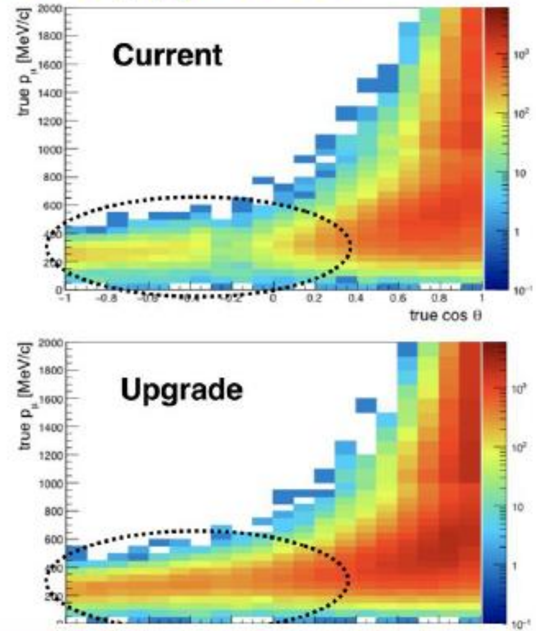
- Stable operat
  years—maxed
- Upgrade bea
  - Most impr
    2.48 s→1
  - Some imp
    pulse
- Associated im
  tat
  d
  or
  review by JPARC; plan to complete
  y 2022

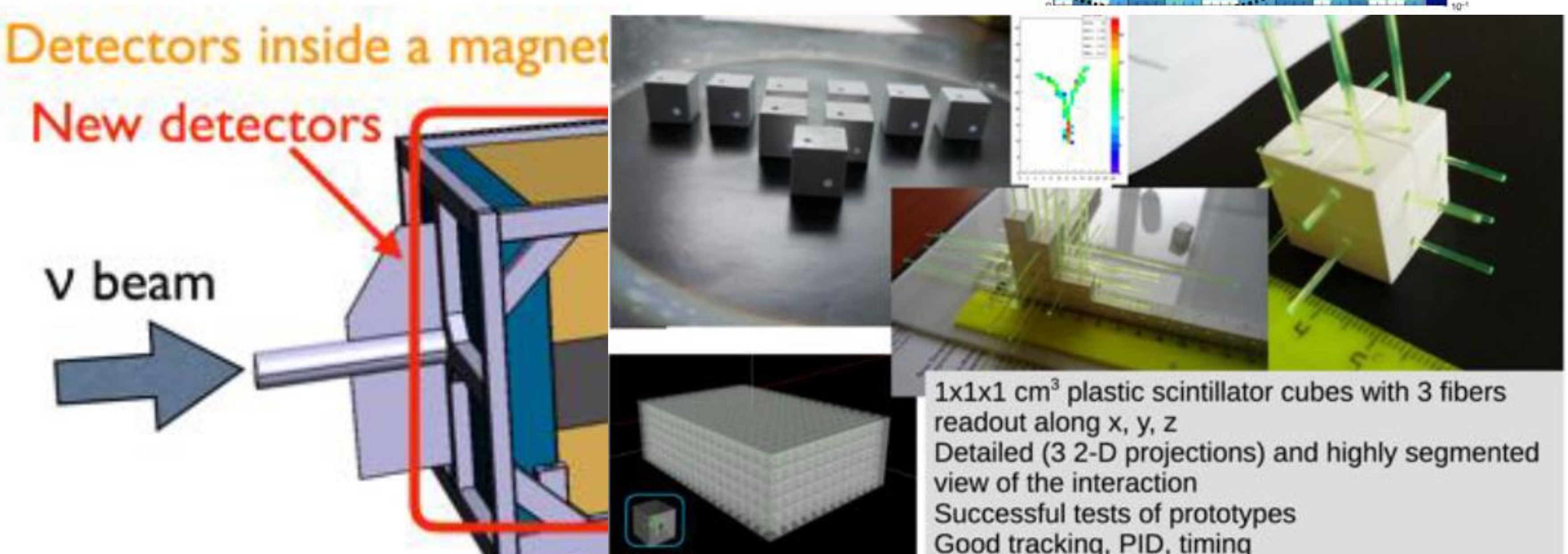




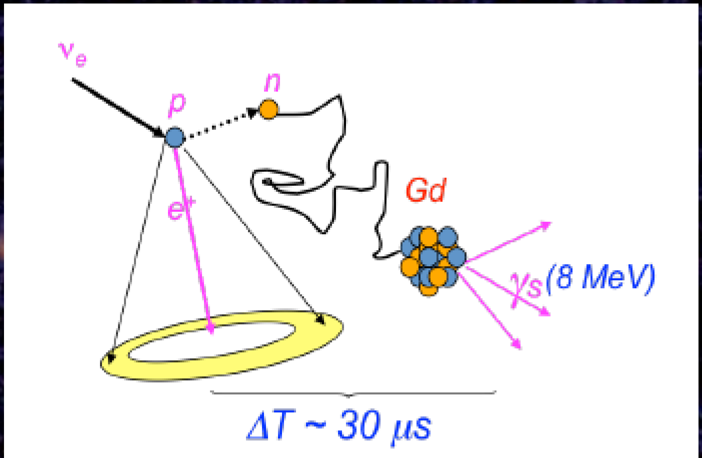
ND280 Upgrades

- Reduce ND systematics to <4%
  - Improve acceptance for high-angle and backwards tracks
- Replace P0D with : superFGD + 2 High-Angle TPCs + TOF
- CERN joined upgrade team in 2018
- Upgrade TDR under review now
- Plan to install in late 2021

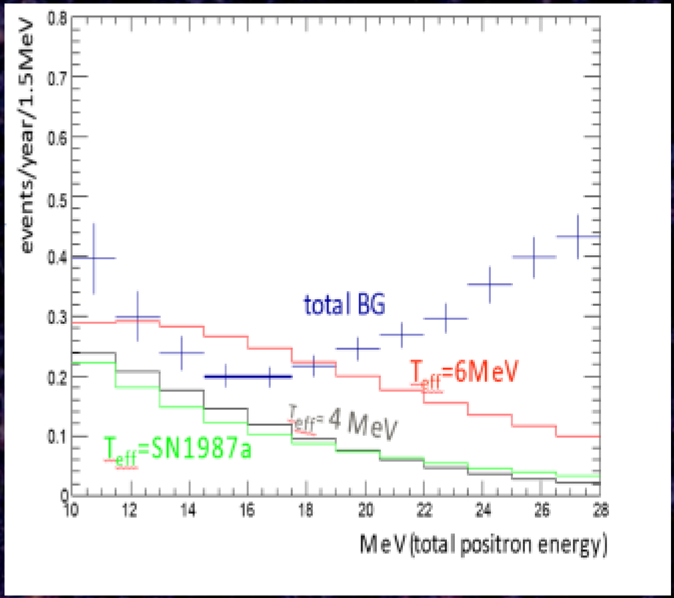




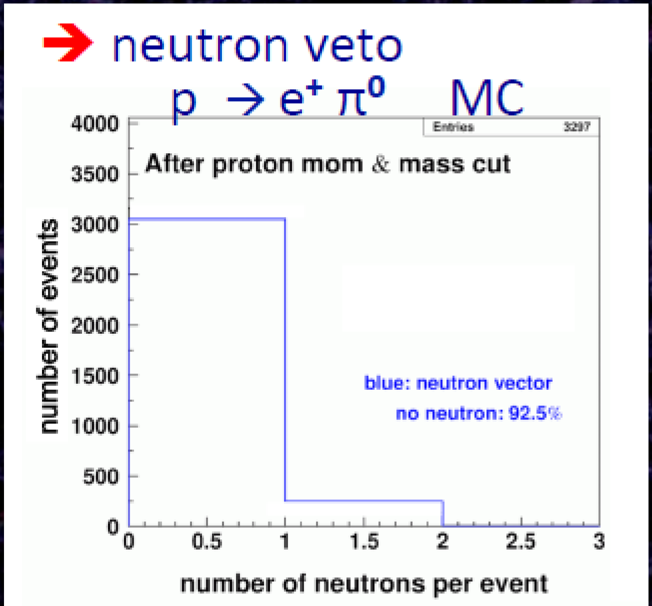
Meanwhile, in Super-K…



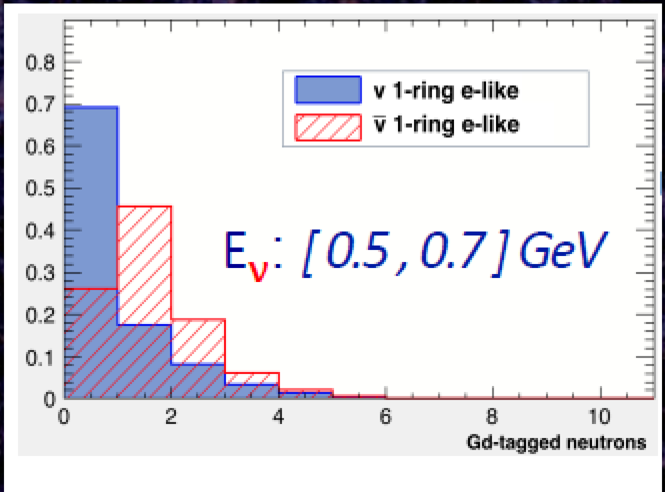
Find DSNR neutrinos. . .



Slash PDK background. . .

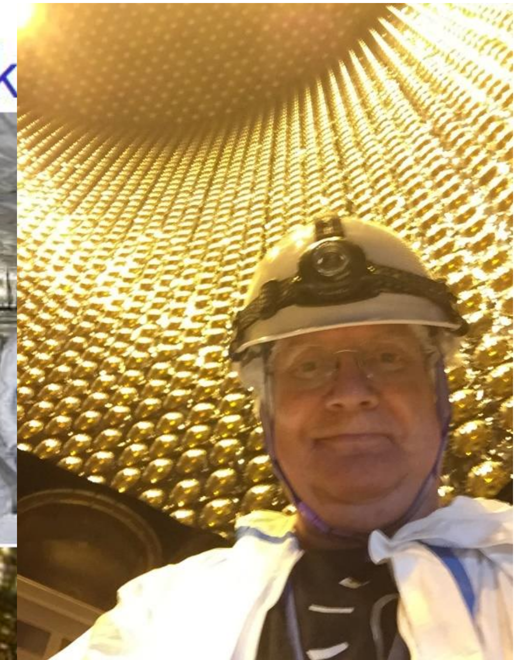


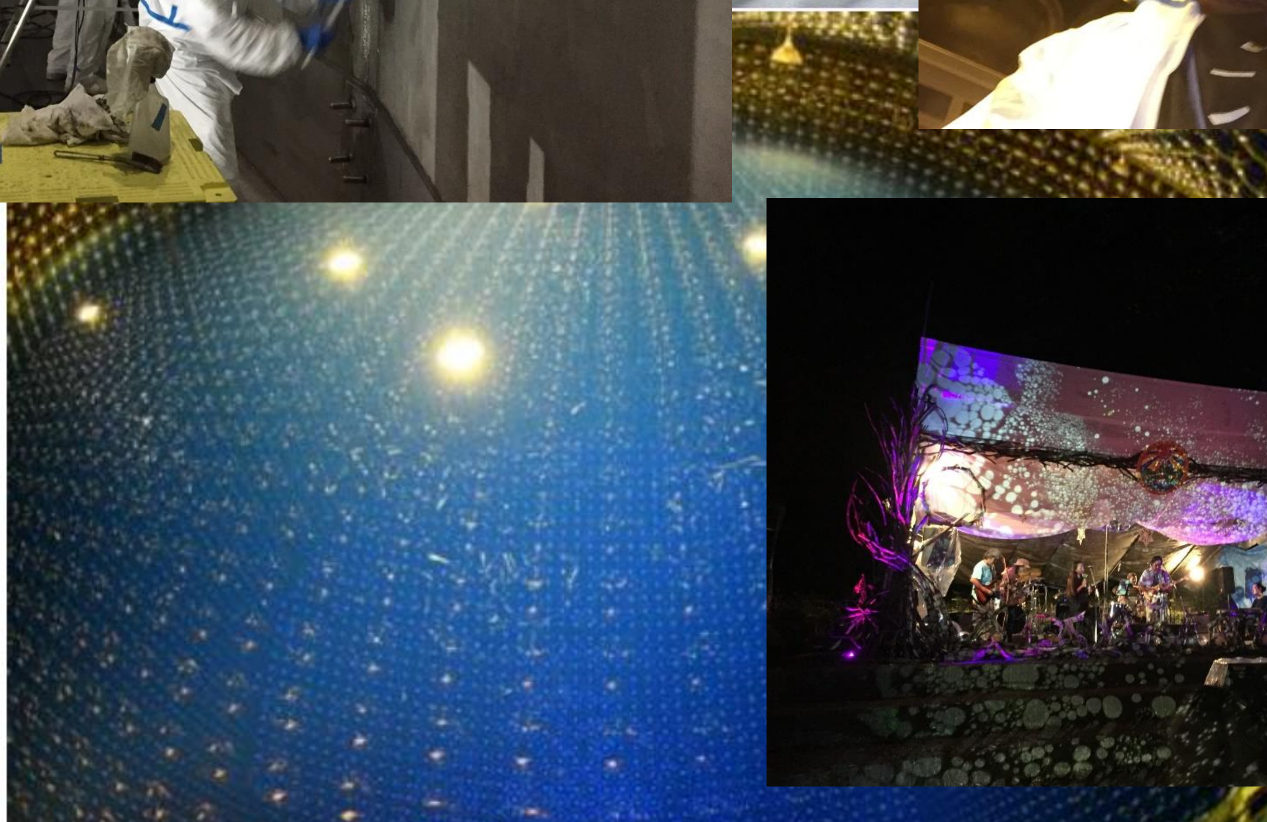
Tell ν from anti-ν. . .



Dave Wark
Oxford U./RAL

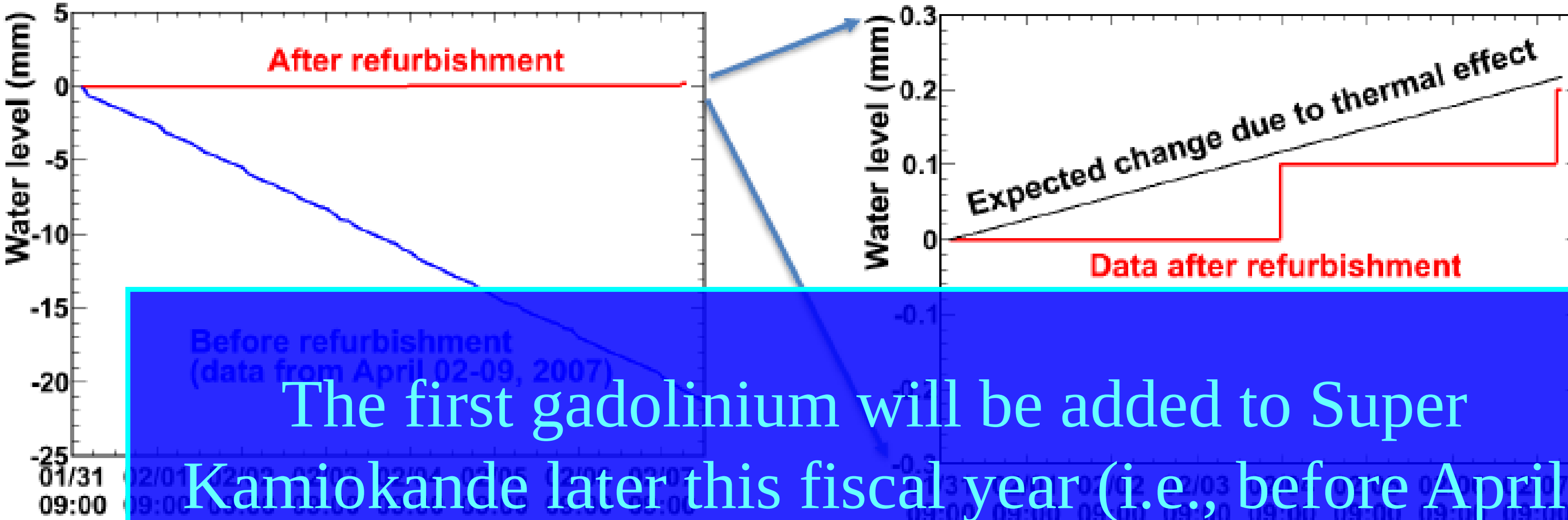
Tank





Water Leakage from SK tank

After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)



The first gadolinium will be added to Super Kamiokande later this fiscal year (i.e., before April 2020).

Conclusion

- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.

NOνA

A broad physics scope

Using $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ ...

- Determine the **ν mass hierarchy**
- Determine the **θ_{23} octant**
- Constrain δ_{CP}

Using $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$ ...

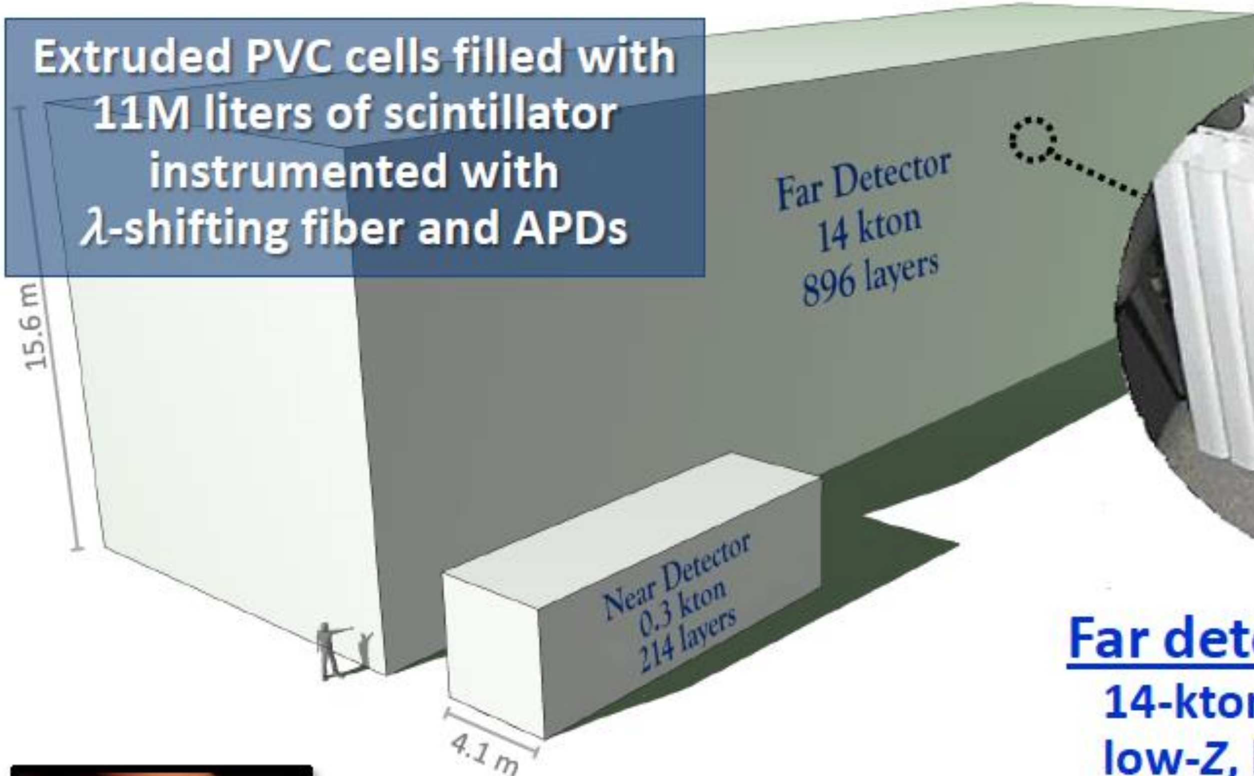
- Precision measurements of $\sin^2 2\theta_{23}$ and Δm^2_{32}.
  (*Exclude* $\theta_{23} = \pi/4$?)
- **Over-constrain** the atmos. sector (*four oscillation channels*)

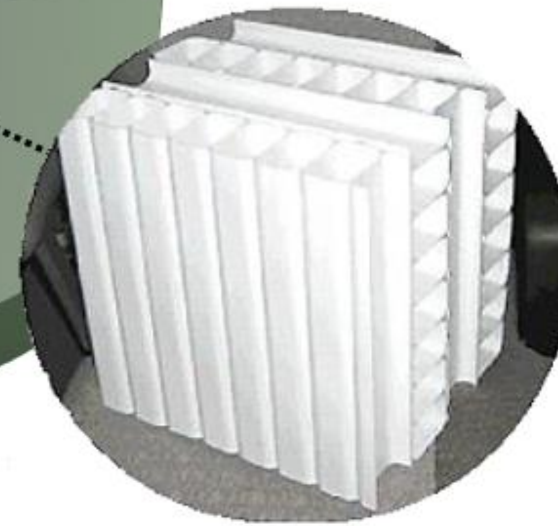
Also ...

- Neutrino cross sections at the NOνA Near Detector
- Sterile neutrinos
- Supernova neutrinos
- Other exotica

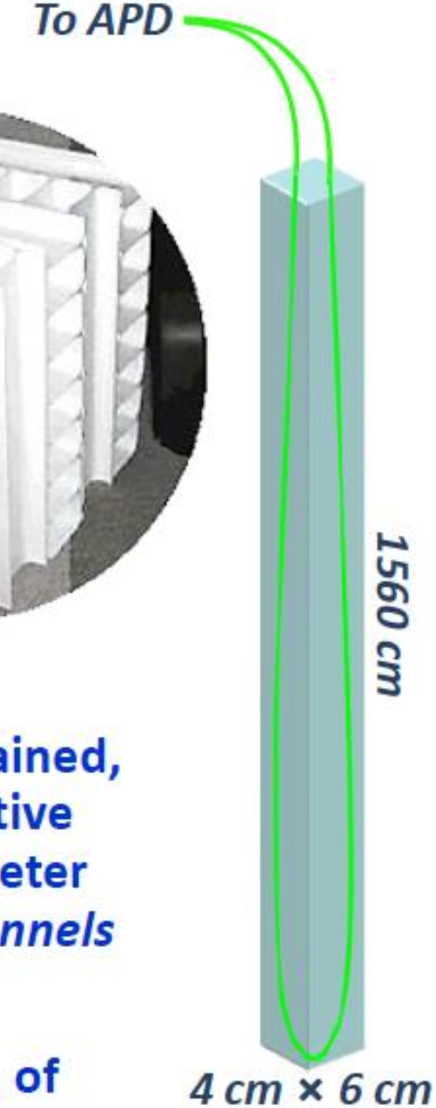
NOνA detectors

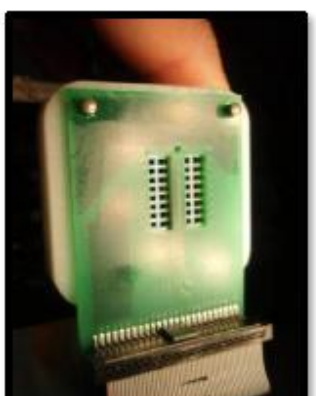
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs





A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

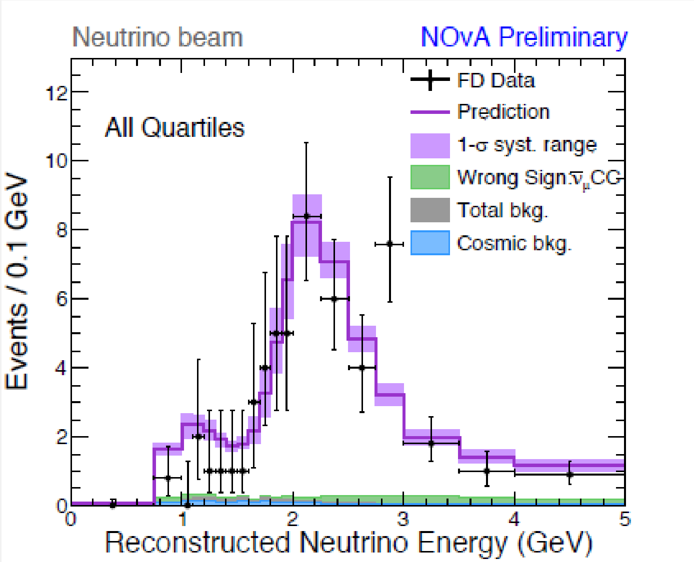
Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ ***344,000 channels***

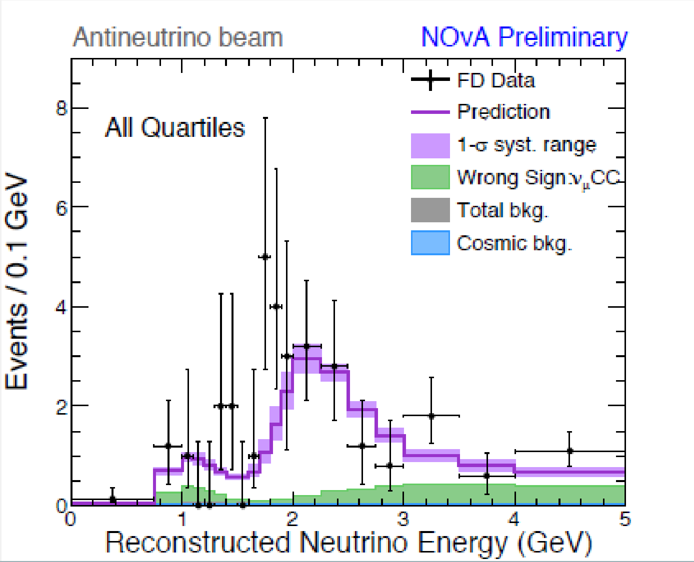
Near detector:

0.3-kton version of the same
→ ***20,000 channels***

MUON (ANTI)NEUTRINO DISAPPEARANCE RESULTS

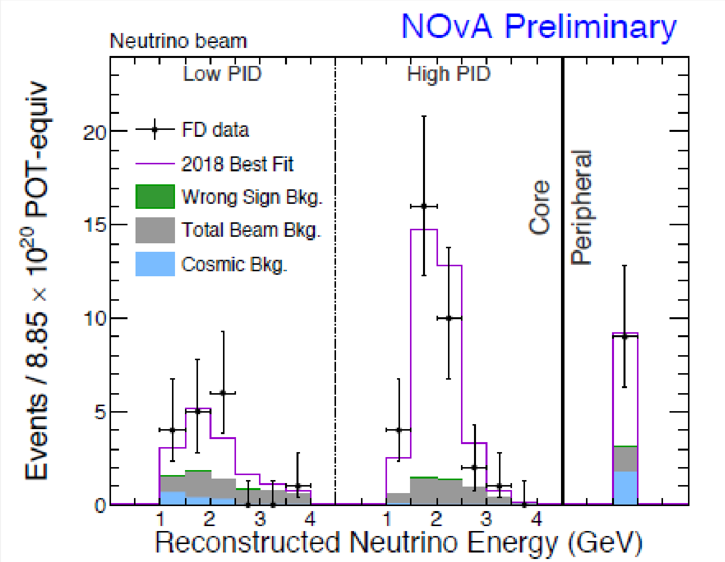


Observed	113
Best Fit Integral	121
Cosmic Background	2.1
Beam Background	1.2
Un-oscillated Prediction	730

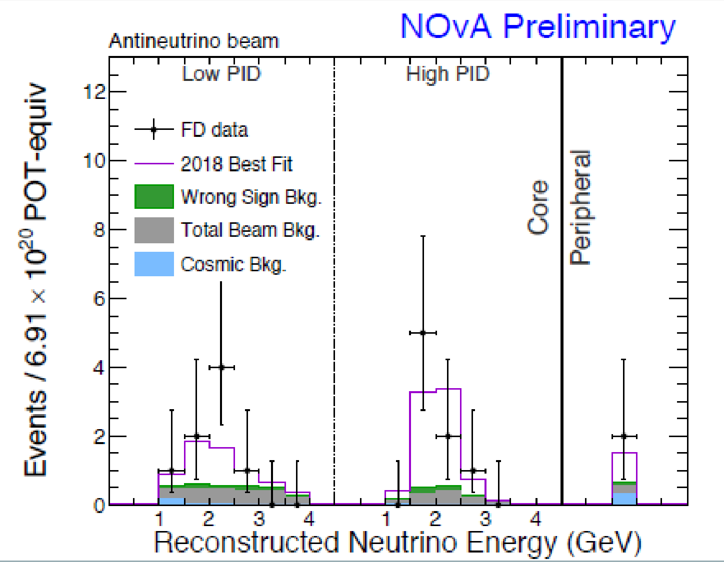


Observed	65
Best Fit Integral	50
Cosmic Background	0.5
Beam Background	0.6
Un-oscillated Prediction	266

ELECTRON (ANTI)NEUTRINO APPEARANCE RESULTS



Observed	58
Best Fit Prediction	59
Cosmic Background	3.3
Beam Background	11.1
Wrong Sign Background	0.7

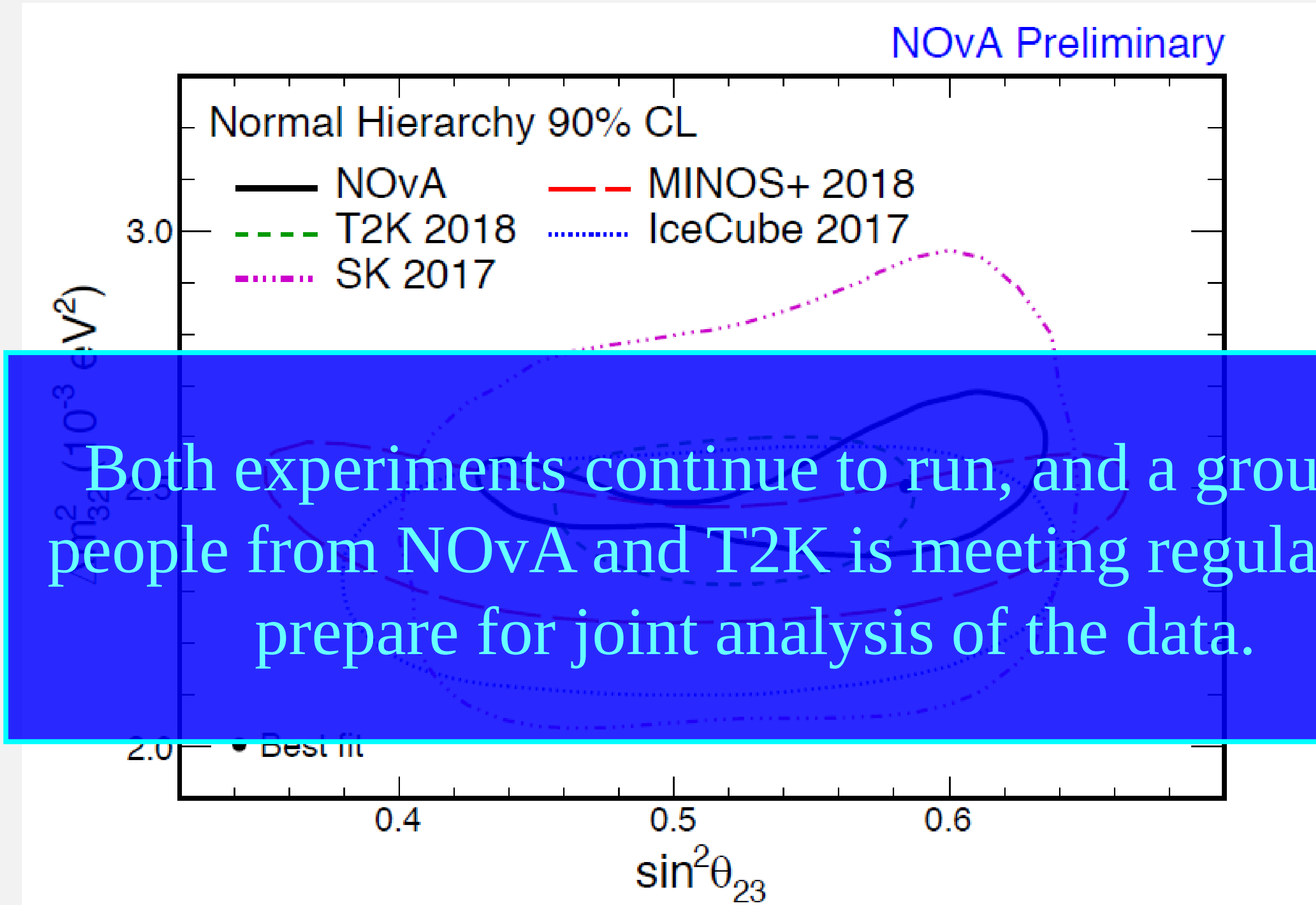


Observed	18
Best Fit Prediction	15.9
Cosmic Background	0.7
Beam Background	3.5
Wrong Sign Background	1.1

Dave Wark
Oxford U./RAL

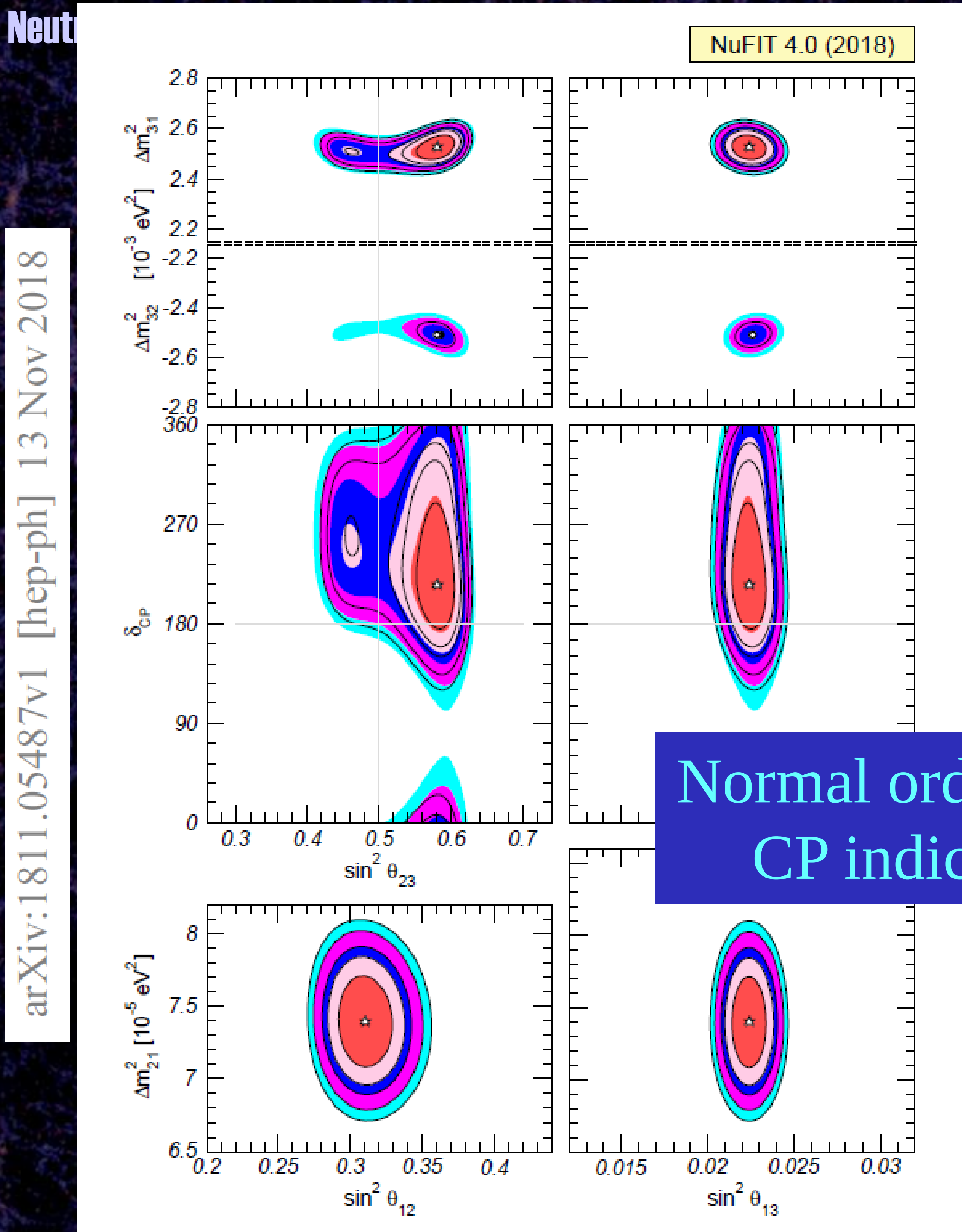
ALLOWED REGION OF PARAMETERS

- NOvA is consistent with other long baseline and atmospheric neutrino experiments.



Both experiments continue to run, and a group of people from NOvA and T2K is meeting regularly to prepare for joint analysis of the data.

Neutr



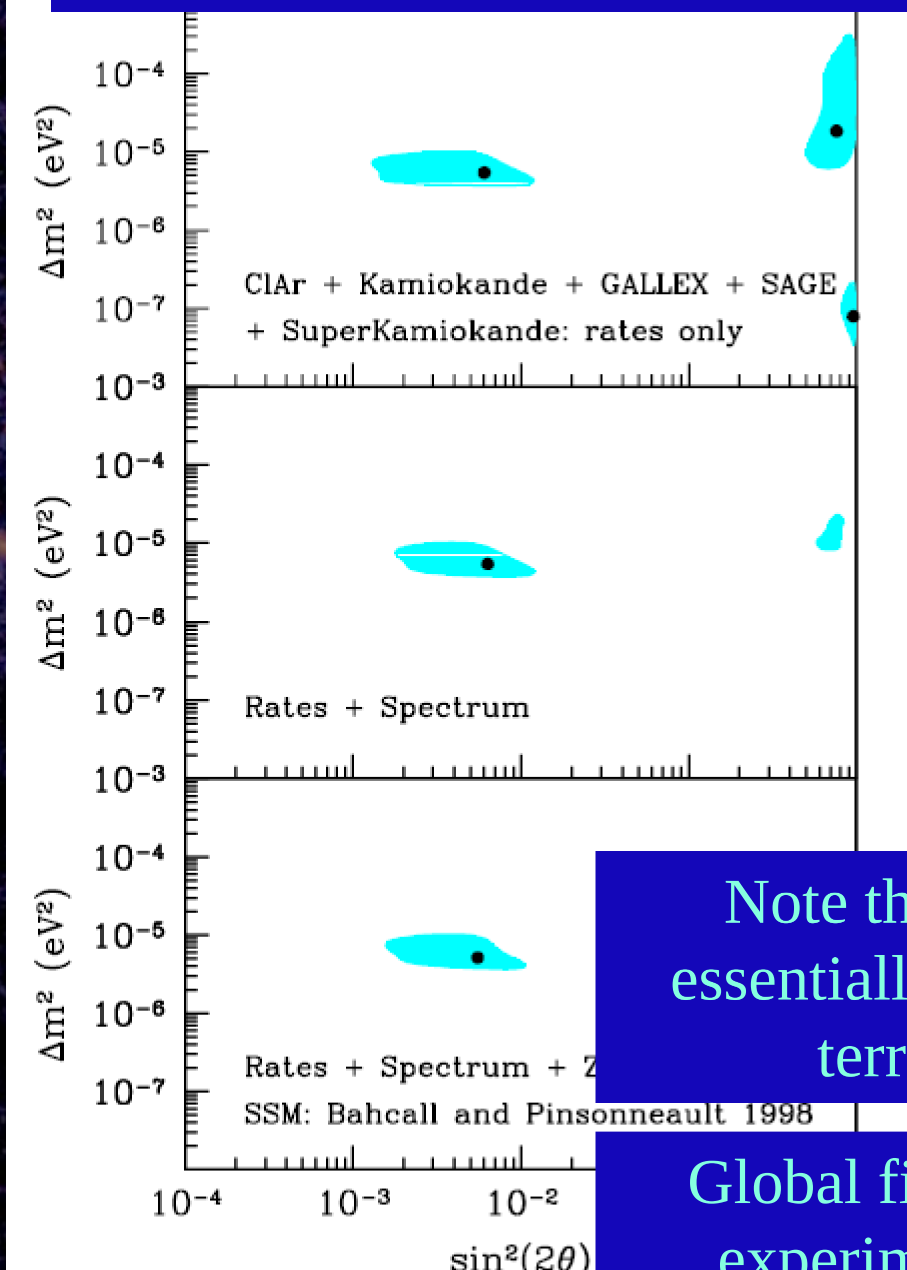
Normal ordering preferred at ~2σ, CP indications much weaker.

Dave Wark
Oxford U./RAL

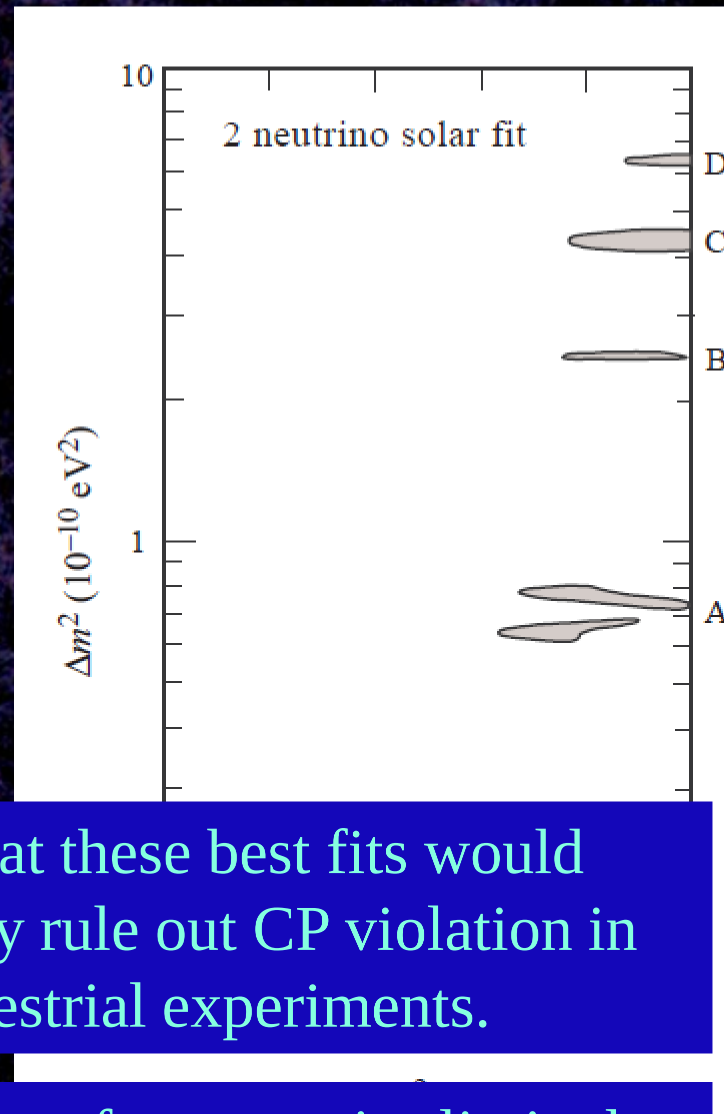
These are 99% c.l. contours!

Using all data as of Neutrinos ‘98.

arXiv:hep-ph/9905458v1 24 May 1999



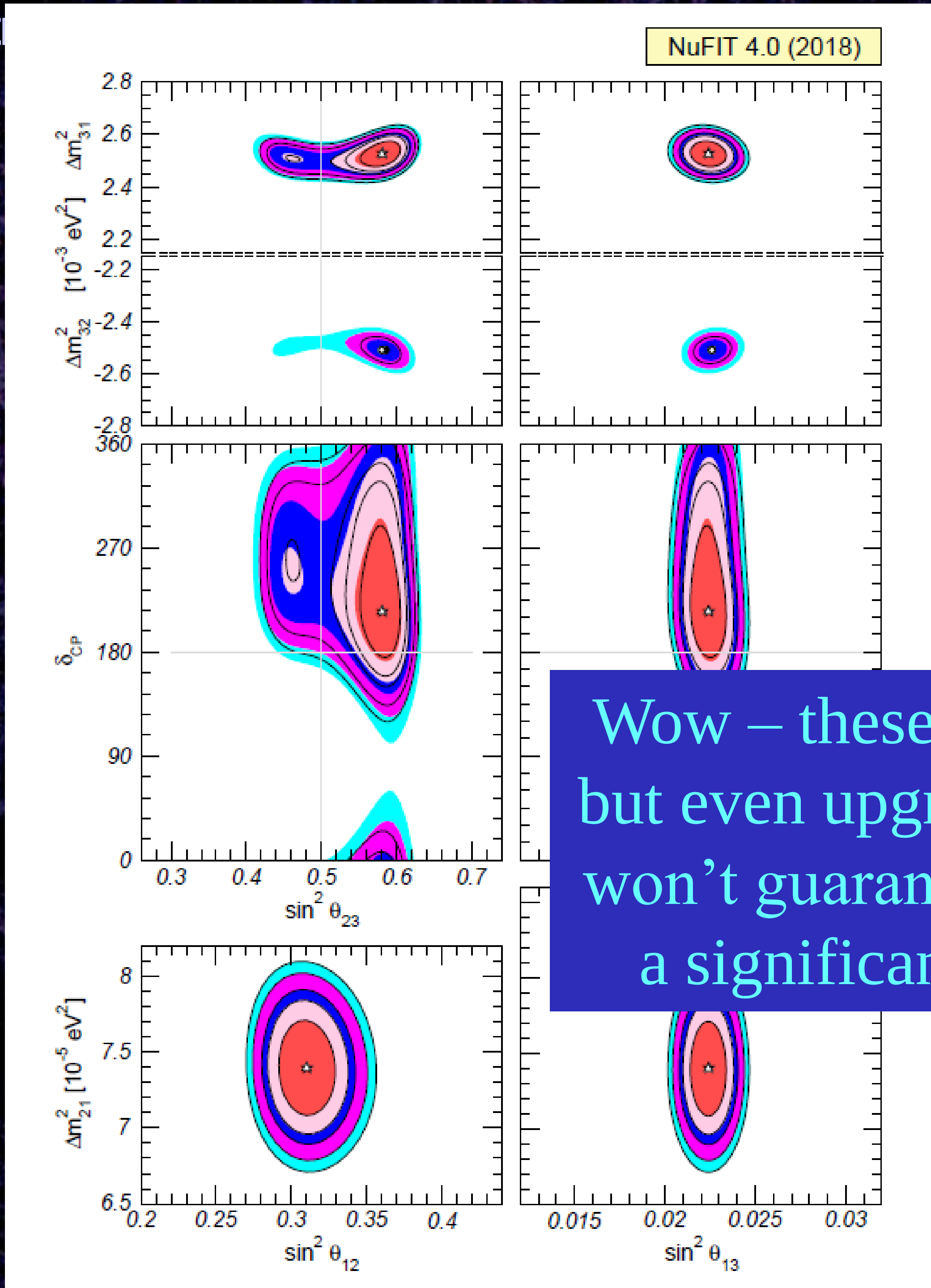
arXiv:hep-ph/9812273v3 24 Feb 1999



Note that these best fits would essentially rule out CP violation in terrestrial experiments.

Global fits of systematics limited experiments will not save you!

Neutr



Wow – these experiments are great – but even upgrades to T2K and NOvA won't guarantee 5σ CP sensitivity for a significant range of values of δ.

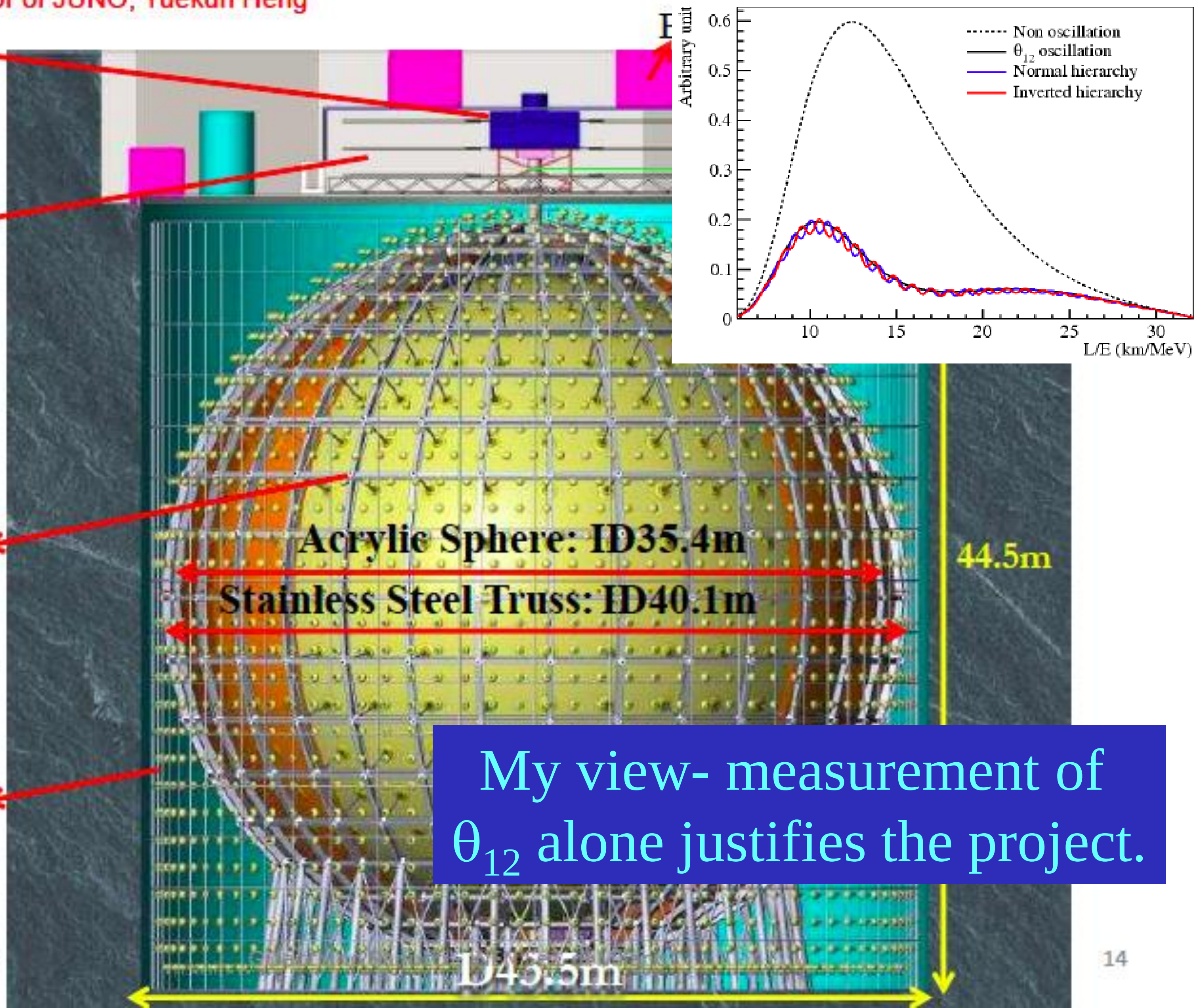
JUNO long baseline reactor experiment

P3.050, Central detector of JUNO, Yuekun Heng

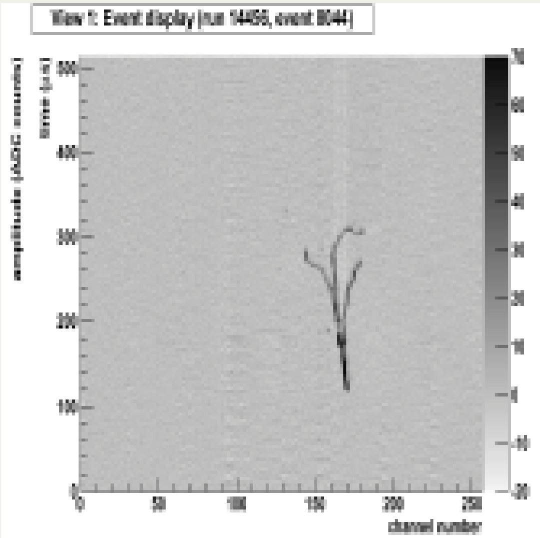
Calibration

Top Tracker

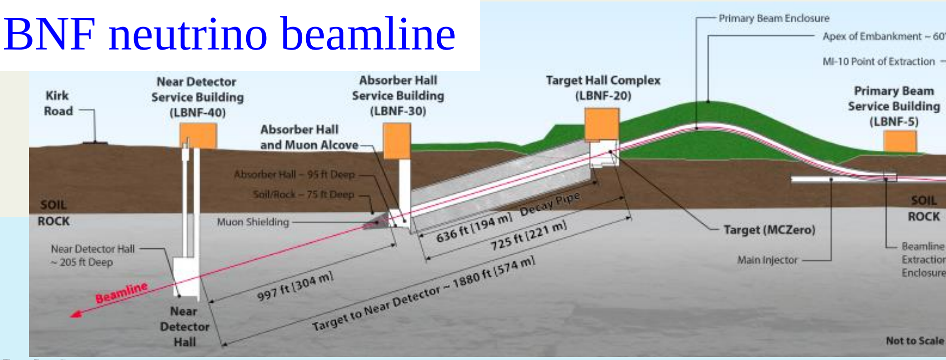
Central detector
Acrylic sphere+
20kt Liquid Scin+
~17000 20" PMT+
~34000 3" PMT
Water Cherenkov
~2000 20" PMT

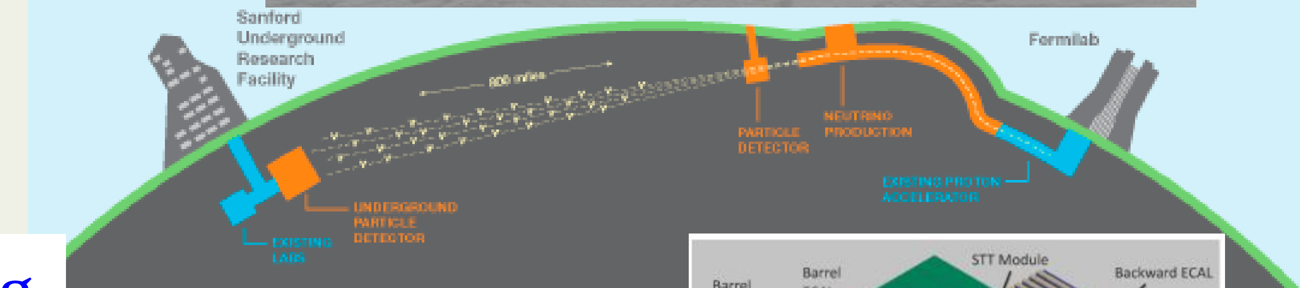


My view- measurement of θ_{12} alone justifies the project.

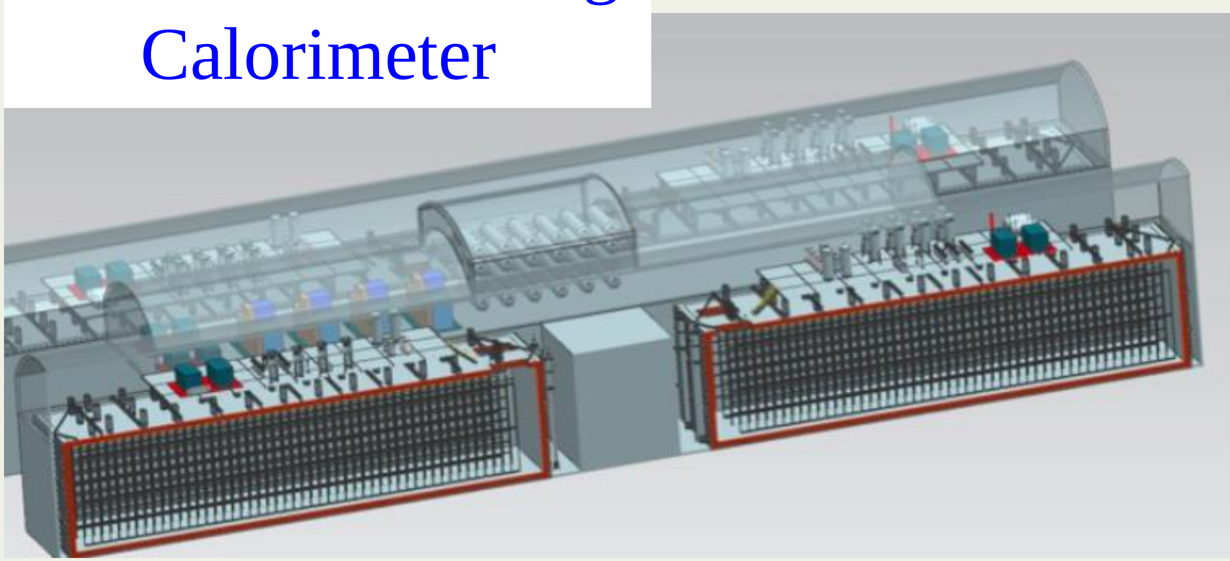


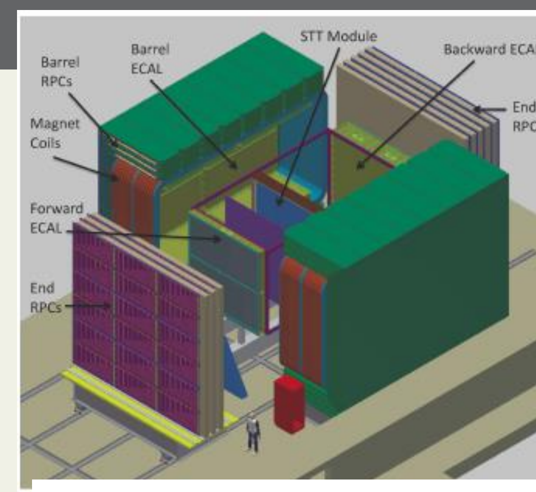
New LBNF neutrino beamline





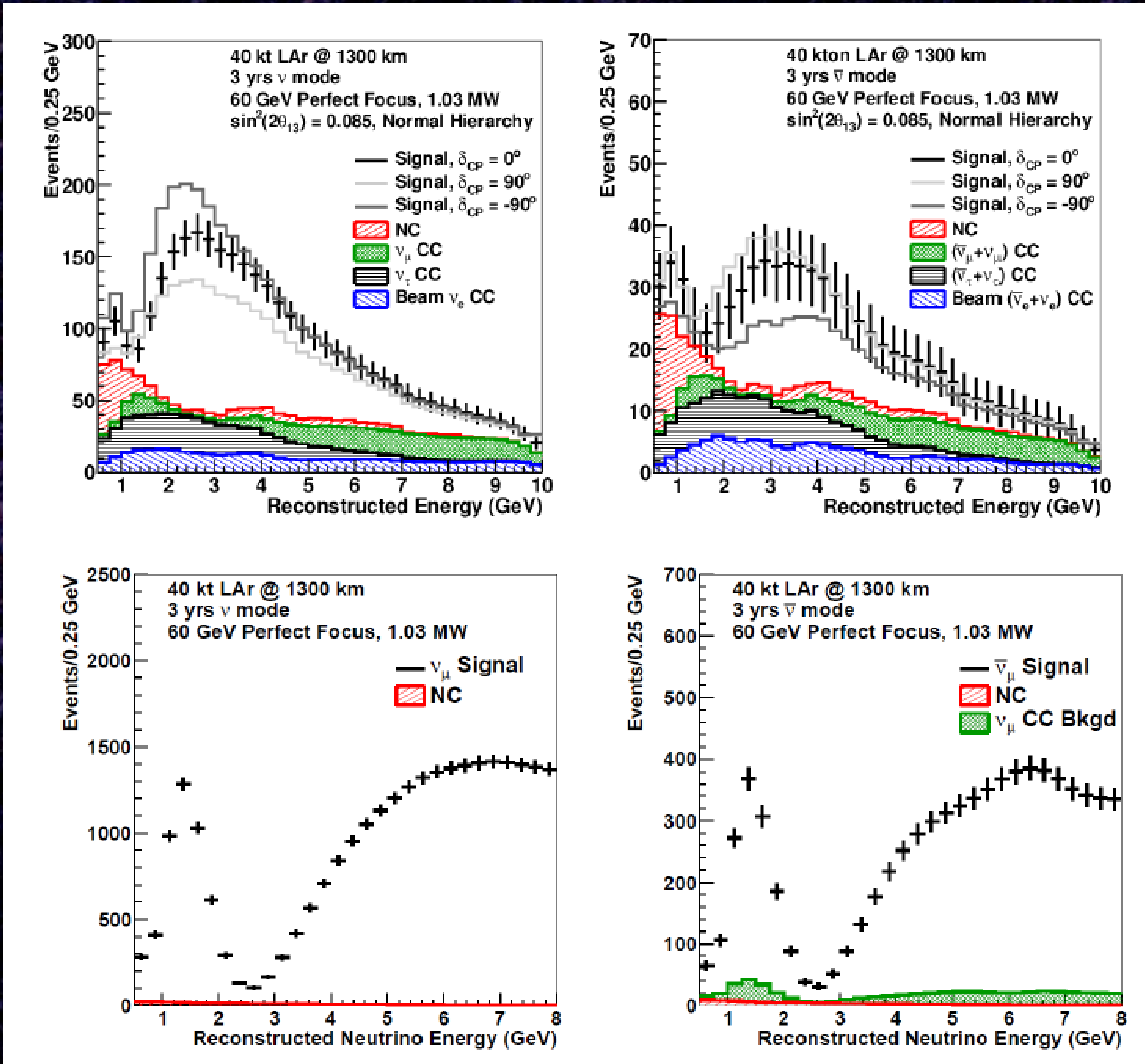
40 kT LAr Tracking Calorimeter





Near Detector @ FNAL

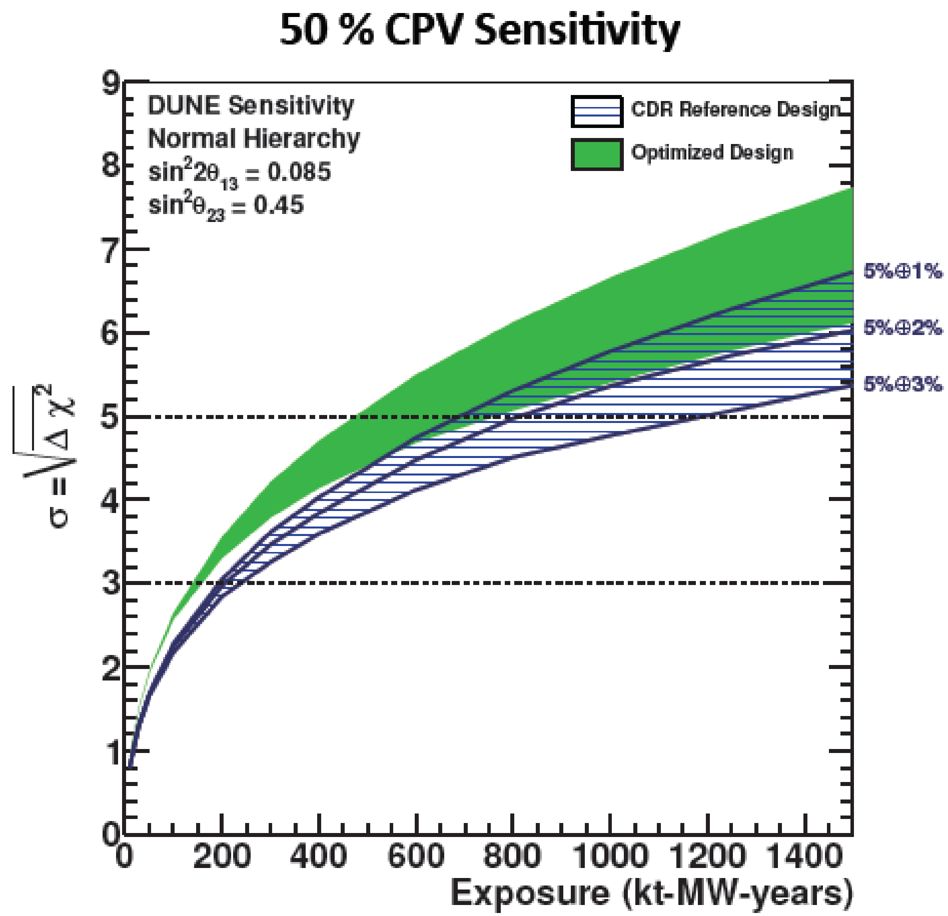
Neutrino Overview



Dave Wark
xford U./RAL

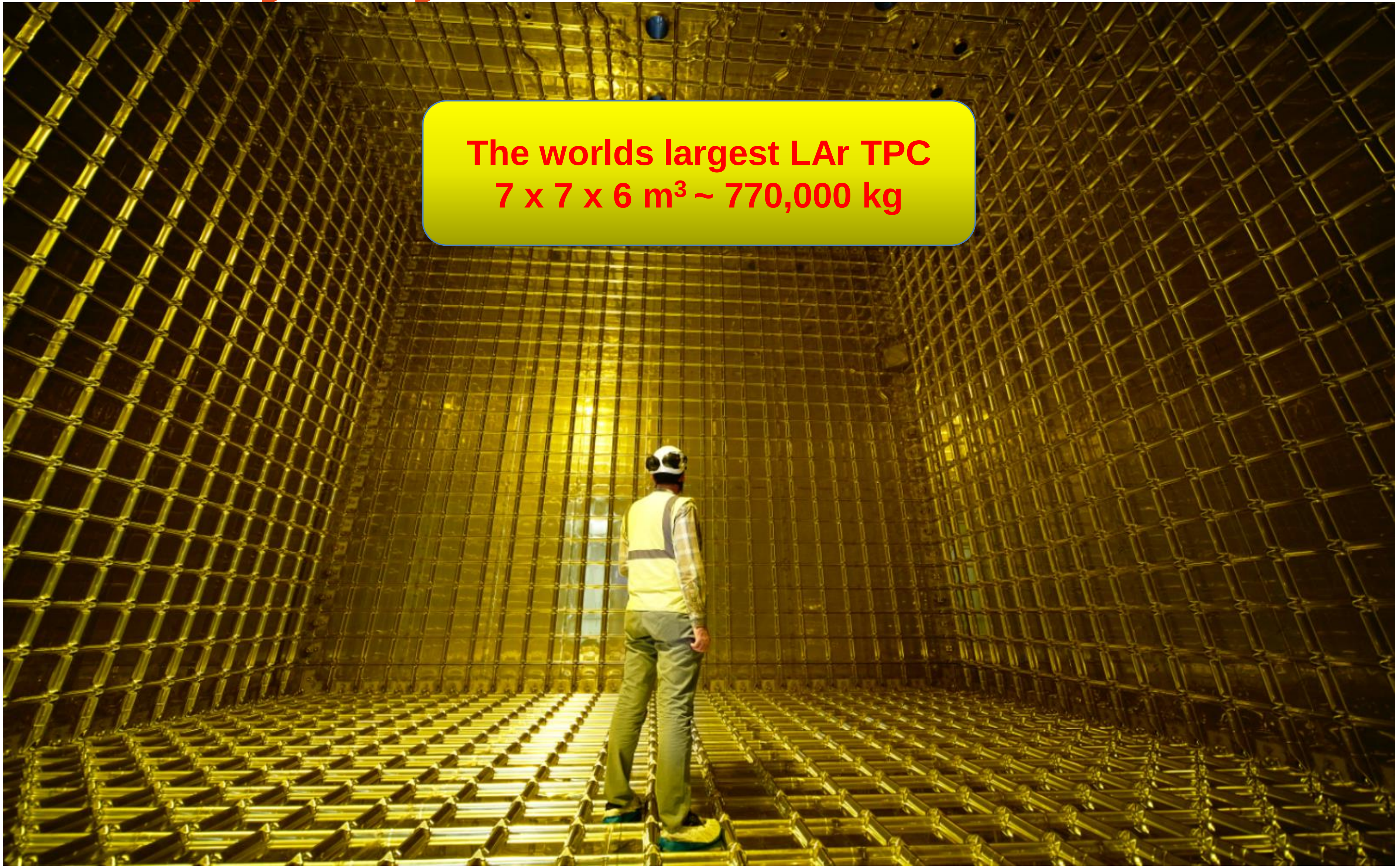
DUNE Sensitivities

Propagate to Oscillation Sensitivities, e.g.

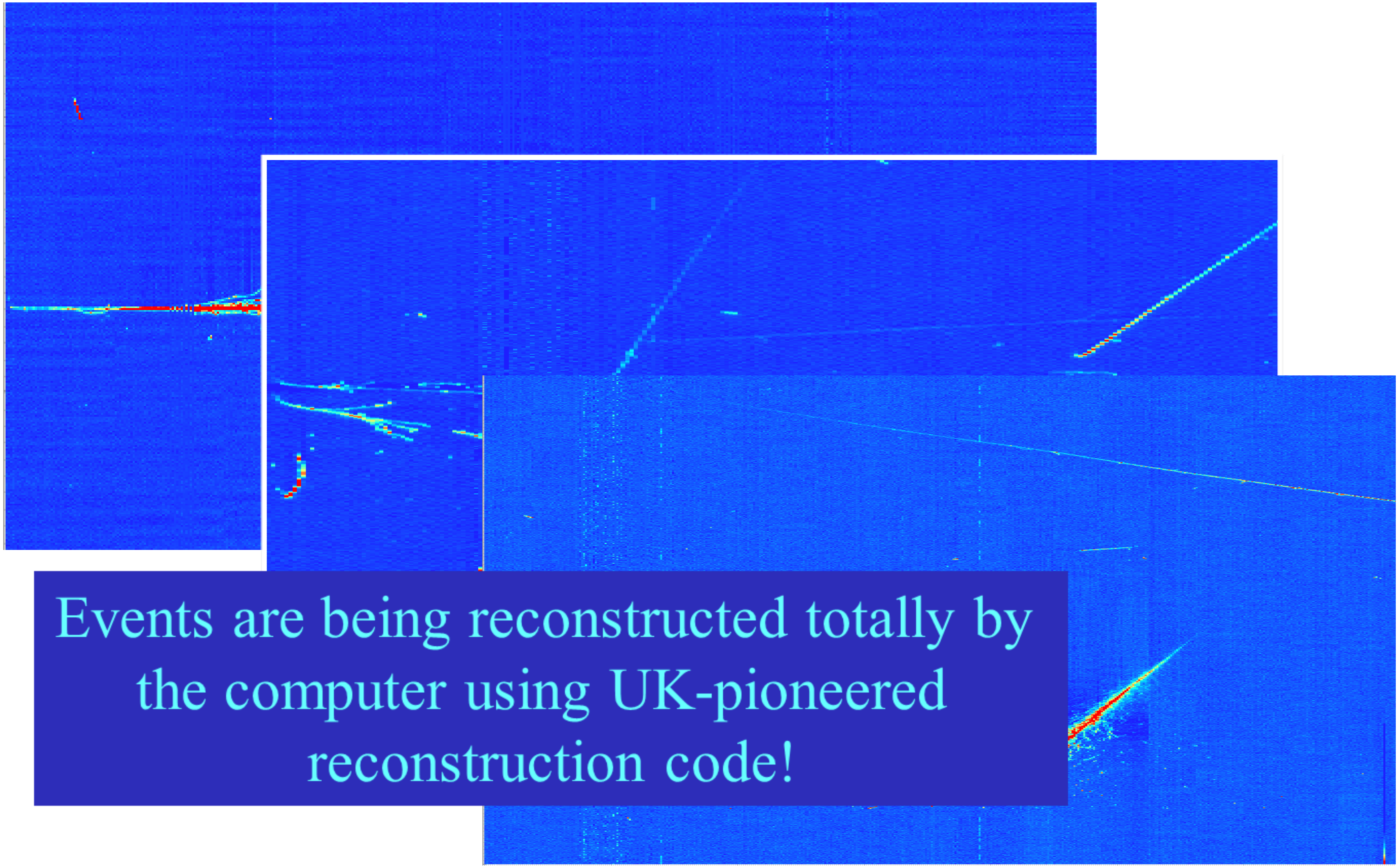


- **Comments**
  - Beam optimization is important
  - For 100–200 kt.MW.years details of systematics are not critical
  - For high exposure, controlling systematics is essential, see 1 – 3 %

Empty Cryostat

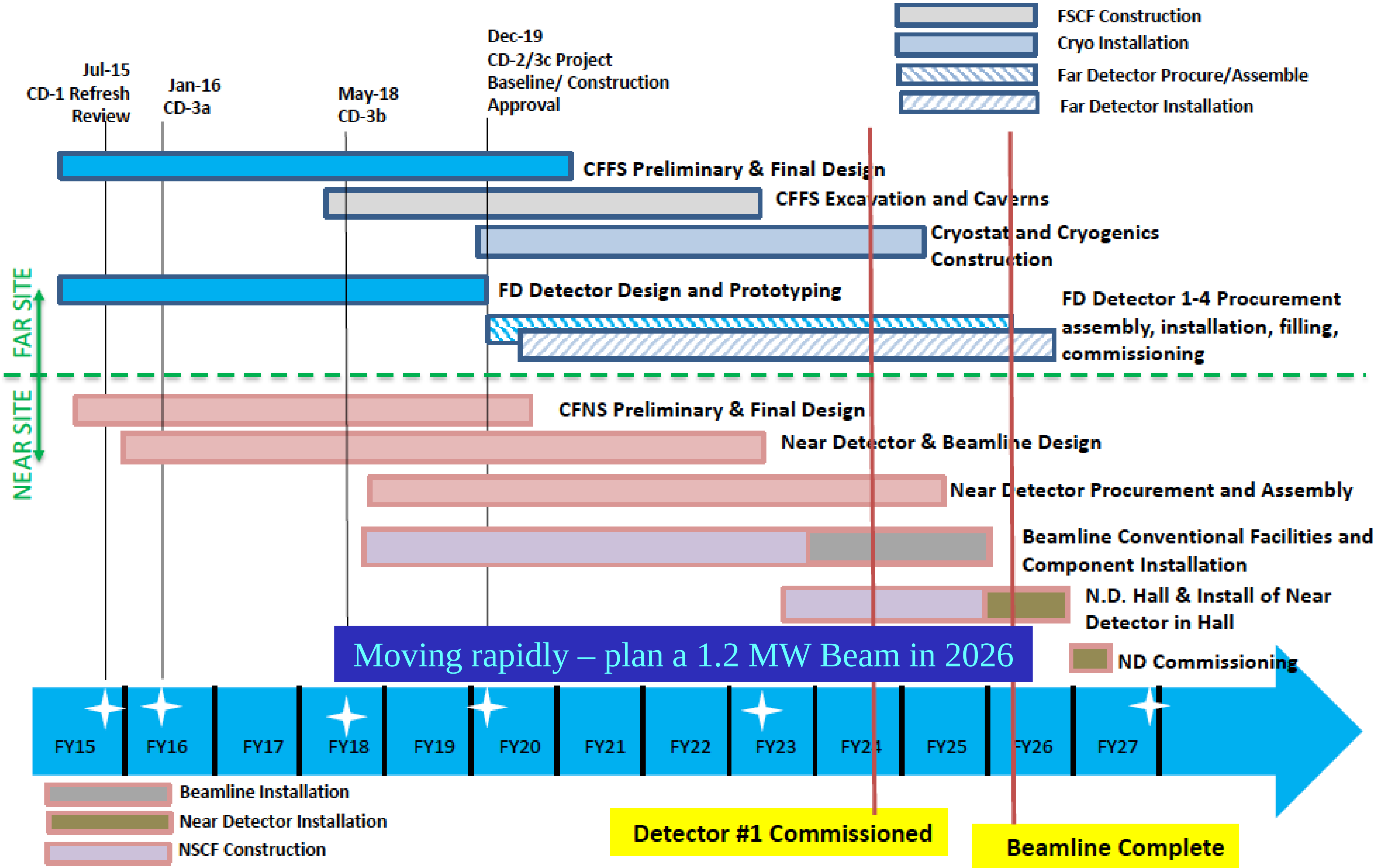


Real Events

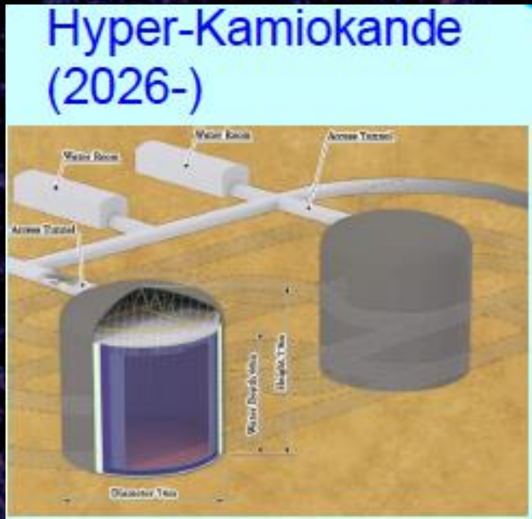


Events are being reconstructed totally by the computer using UK-pioneered reconstruction code!

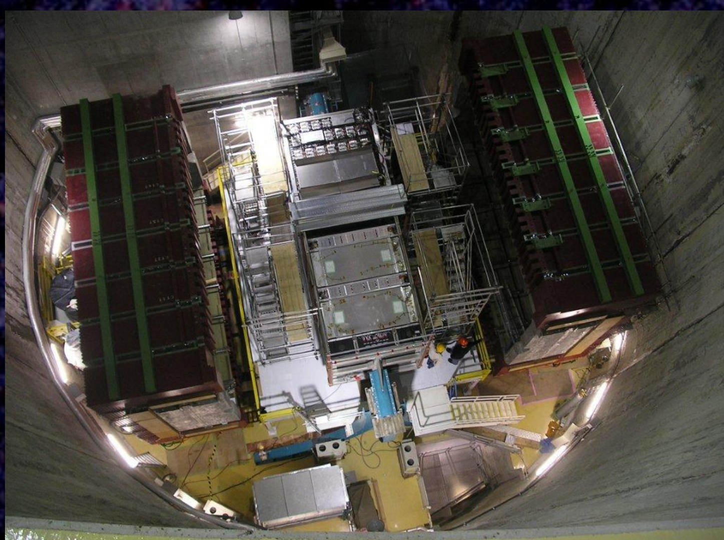
LBNF/ DUNE Schedule Summary Overview



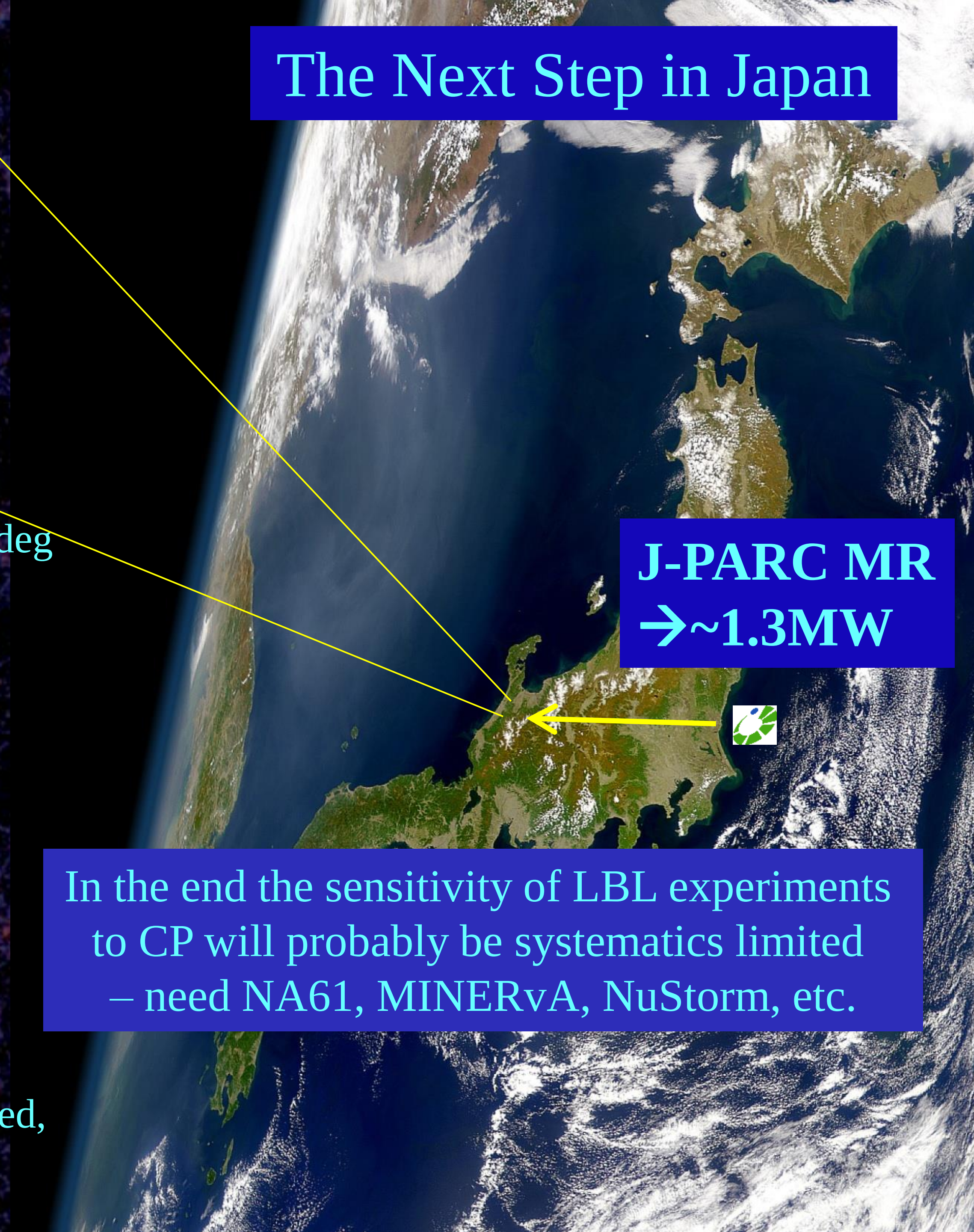
The Next Step in Japan



Hyper Kamiokande L=295km OA=2.5deg
520,000 ton Water Cerenkov Detector!.



T2K 280m near detectors, will be re-used,
but upgraded and enhanced
with new near detector(s) at 2km.

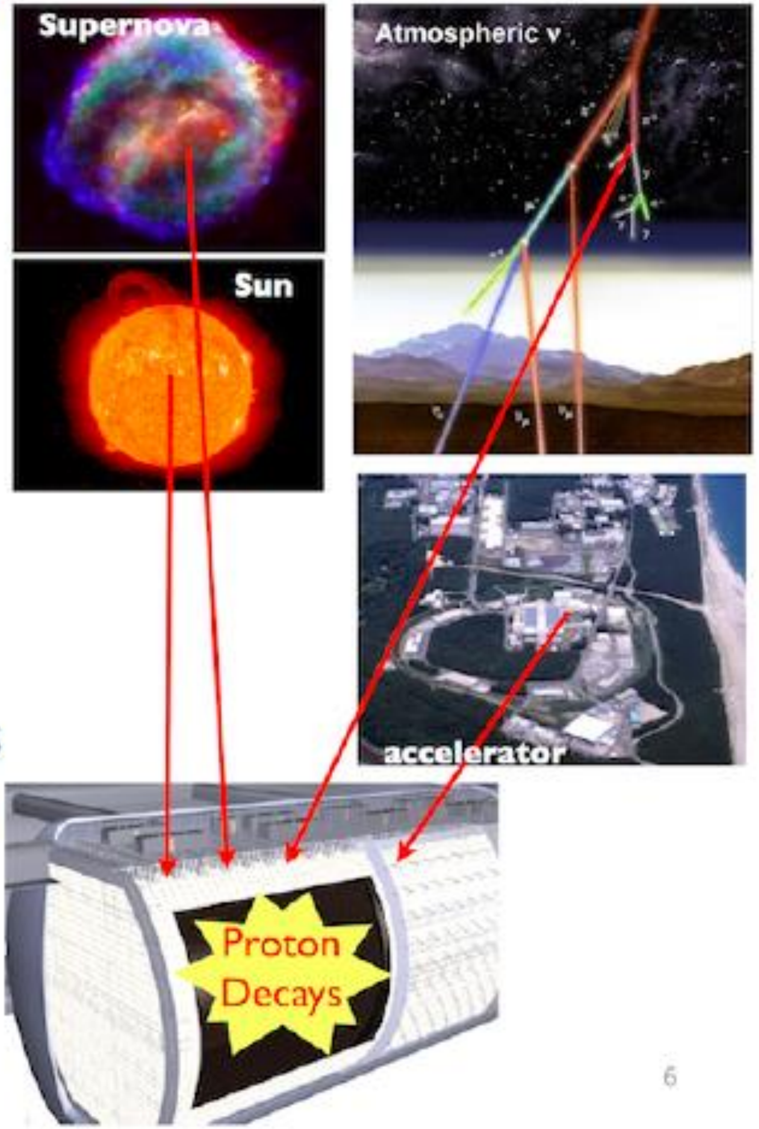


J-PARC MR
→~1.3MW

In the end the sensitivity of LBL experiments to CP will probably be systematics limited – need NA61, MINERvA, NuStorm, etc.

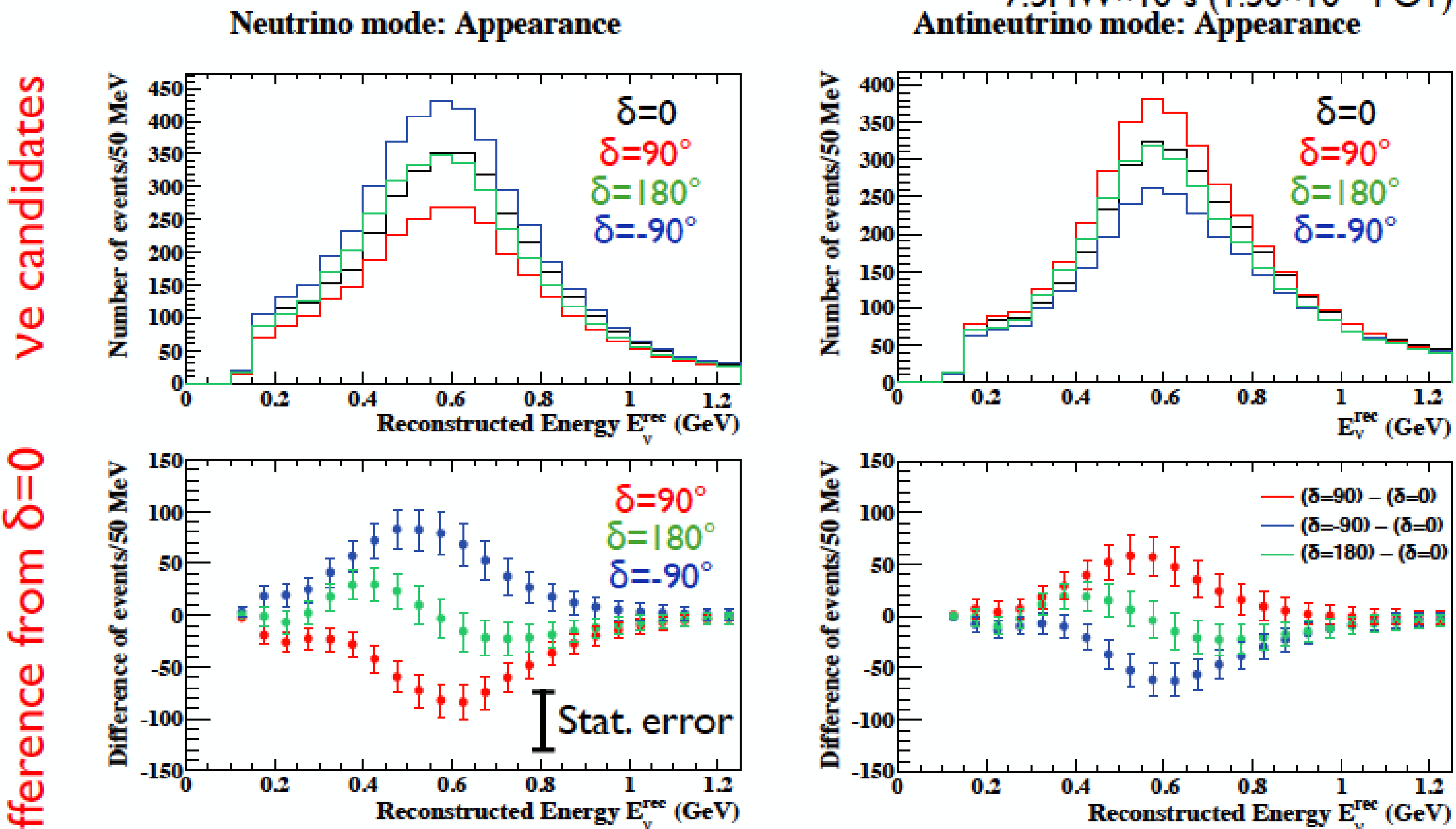
Multi-purpose detector, Hyper-K

- Comprehensive study of ν oscillation
  - CPV (>3σ for 76% of δ)
  - Mass hierarchy with acc.+atm ν
  - θ_{23} octant
  - Test of exotic scenarios
- Nucleon decay discovery potential
  - $e^+\pi^0$: 5×10^{34} years,
    νK^+: 1×10^{34} years (3σ)
- Neutrino astrophysics
  - Supernova up to 2Mpc, ~1SN/10yrs
  - Relic SN neutrinos (~200ν/10yers)
  - Indirect dark matter search
  - Solar neutrino (~200evts/day)
- Geophysics
- Maybe more / unexpected



δ_{CP} dependence of observables

7.5MW×10⁷s (1.56×10²² POT)

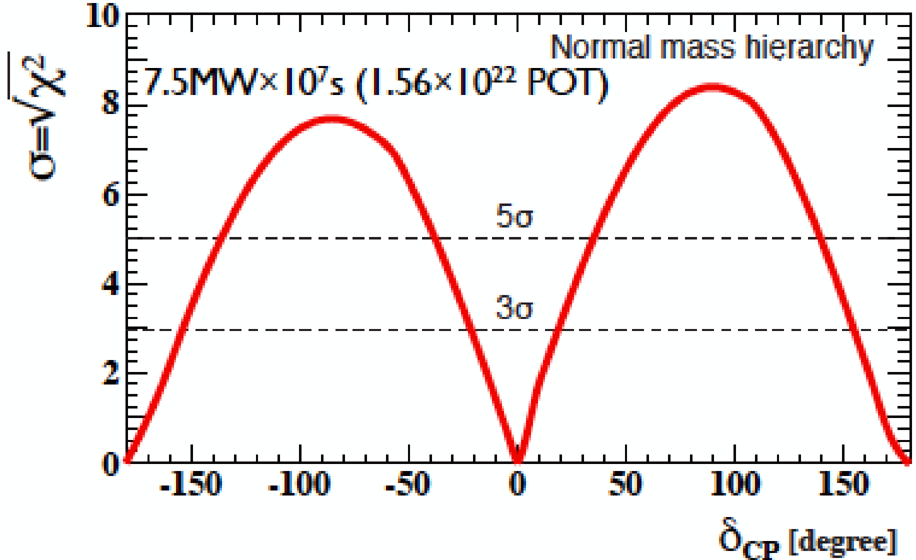


Sensitive to all values of δ with numbers + energy spectrum shape

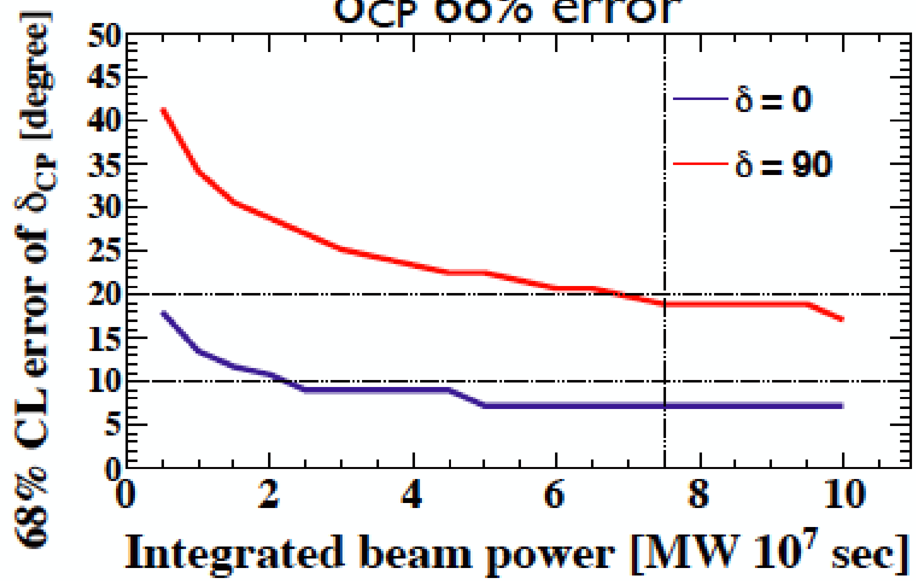
CPV sensitivity

- Excellent sensitivity to CPV
  - >3σ for 78% of δ
  - >5σ for 56% of δ
- From discovery to δ_{CP} measurement:
  - ~9° error possible
  - Test predictions from flavor symmetries, leptogenesis etc
- Study with updated systematics ongoing

$\sin\delta_{CP}=0$ exclusion



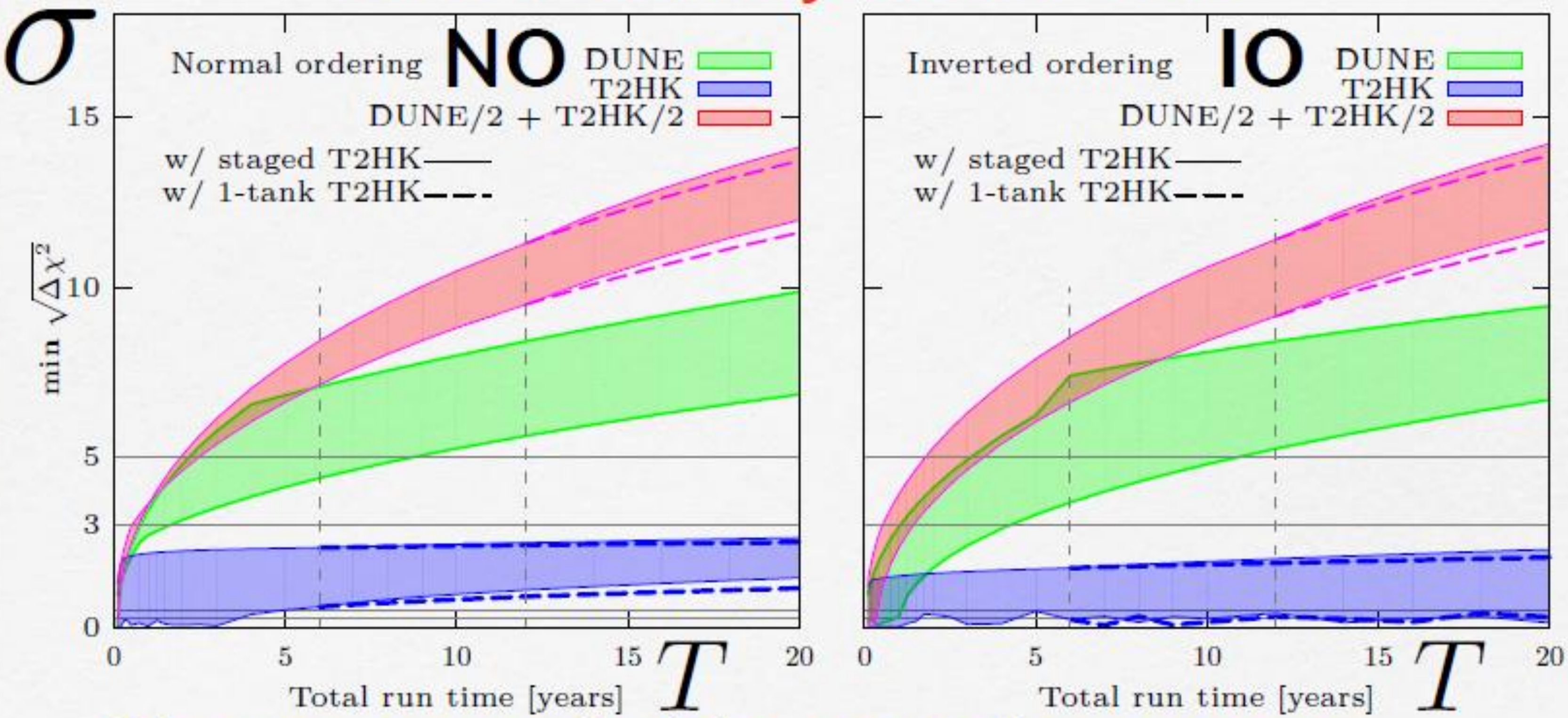
δ_{CP} 68% error



Why do we need both?

Sensitivity to Mass Ordering

Band uncertainty due to theta23

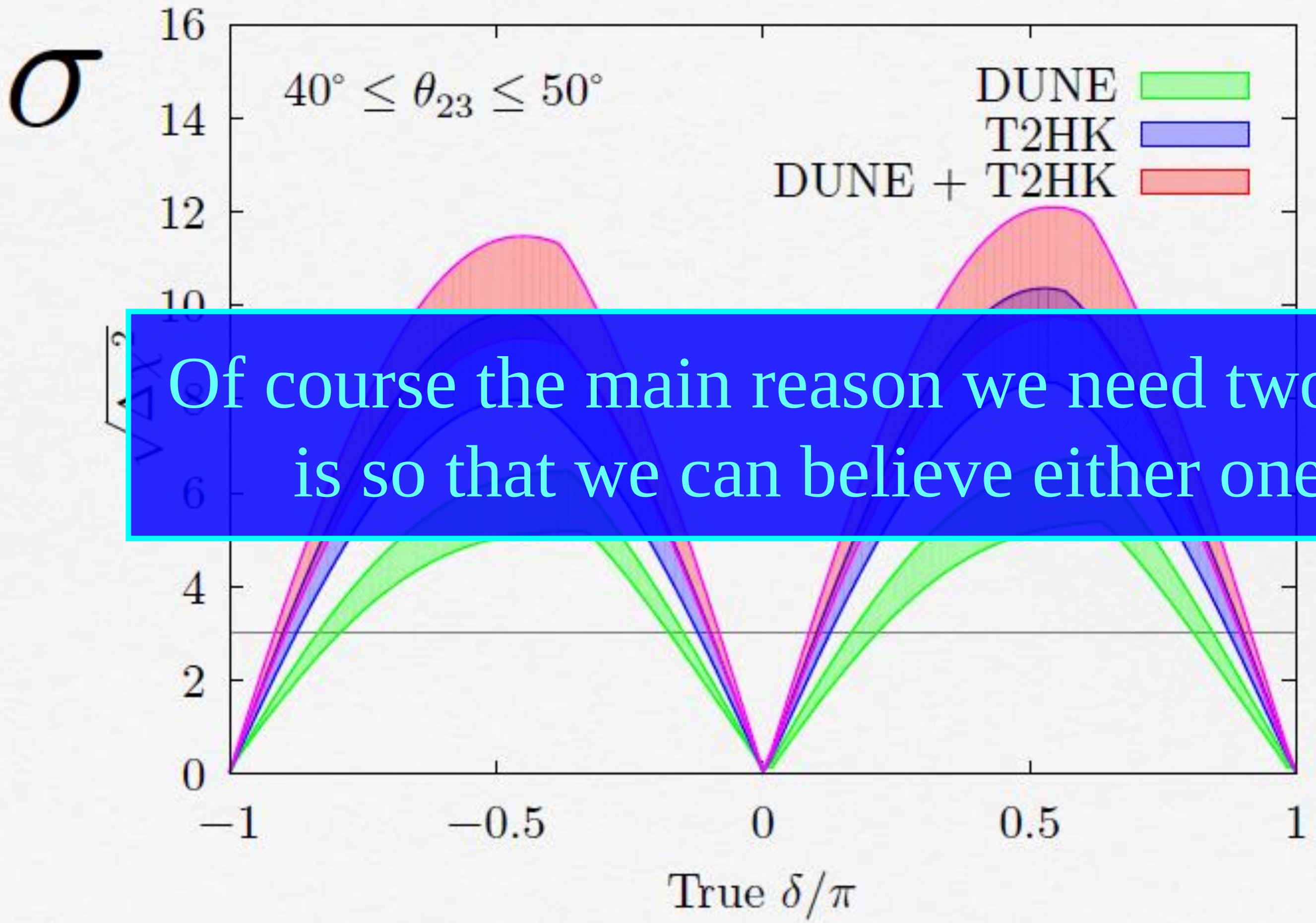


Shows remarkable complementary (statistics are irrelevant after T=5 years)

From Steve King's talk at NuPhys 2016.

Oxford U./RAL

CP violation sensitivity

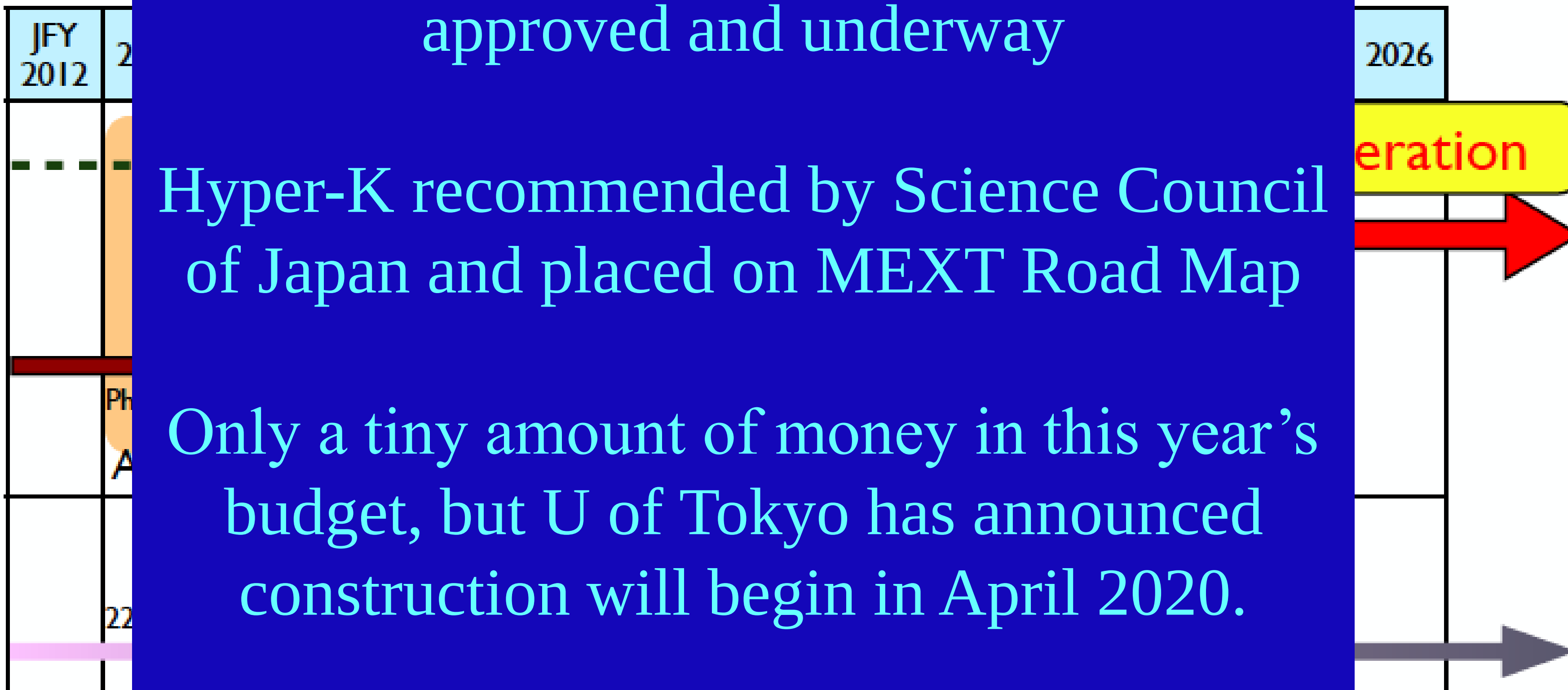


Of course the main reason we need two experiments is so that we can believe either one of them.

Dave Wark
Oxford U./RAL

Hyper-K Target Timeline

Full sur



First power upgrade of JPARC accelerator approved and underway

Hyper-K recommended by Science Council of Japan and placed on MEXT Road Map

Only a tiny amount of money in this year’s budget, but U of Tokyo has announced construction will begin in April 2020.

Stay tuned. . .

~2

~2

~2025 Data taking start

> 2025 Discoveries!

Some Open Experimental Questions in Neutrino Physics

Completing the picture of neutrino oscillations.

- Parker, Nonnenmacher, Sedgwick, Pidcott, Kaboth, Vann

Neutrino masses and nature – Majorana or Dirac?

- Di Valentino, Kroupova, Nirkko, Taylor, Patrick

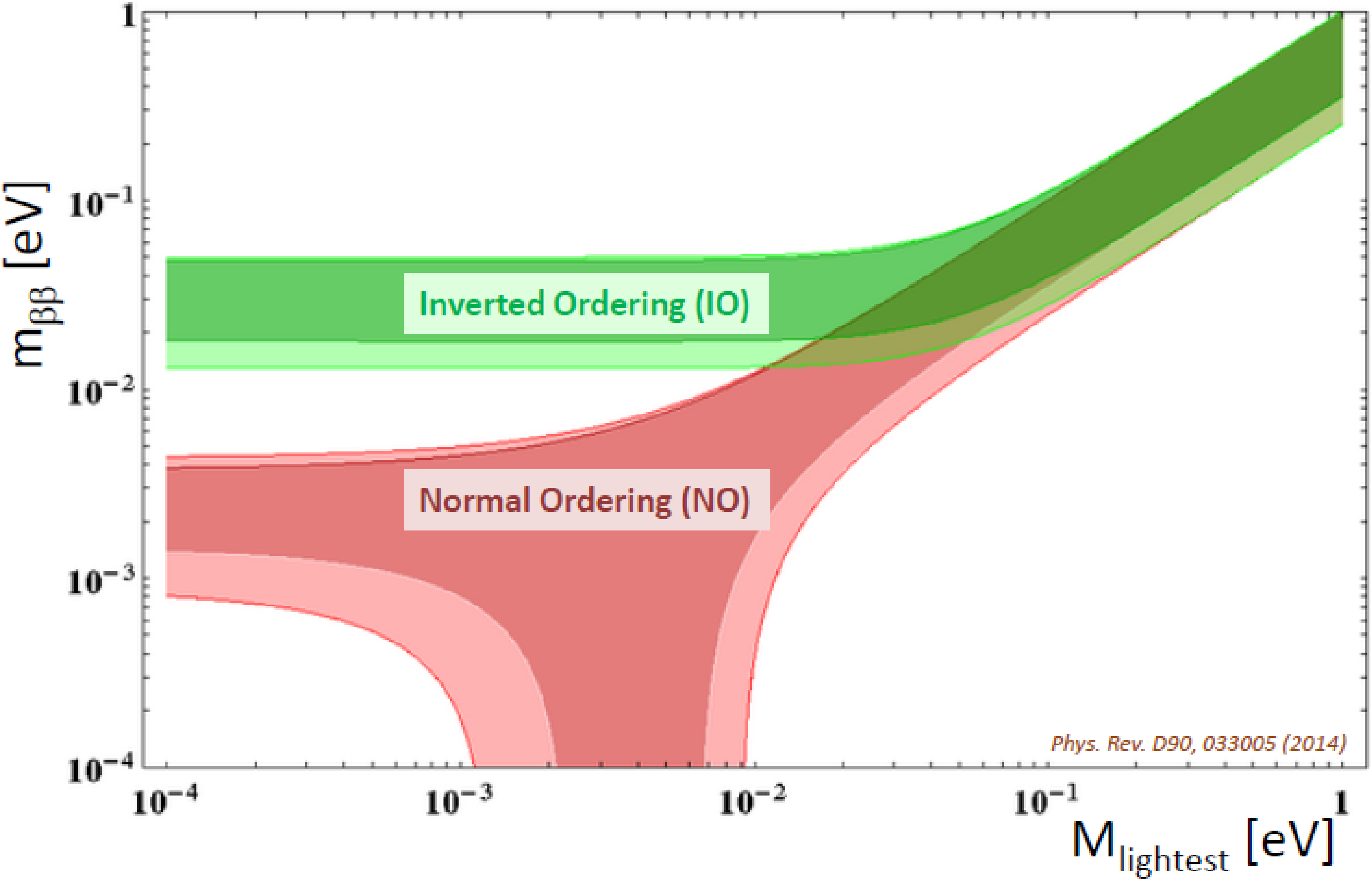
Are there sterile neutrinos?

- Di Valentino, Barker, Boschi, Blake, Van den Pontseele

Using neutrinos as probes.

- Katori, Malek

$m_{\beta\beta}$ distribution in the parameter space



$m_{\beta\beta}$ distribution in the parameter space

Phys. Rev. D 96, 053001 (2017) (see also *Phys. Rev. D 96, 073001 (2017)*)

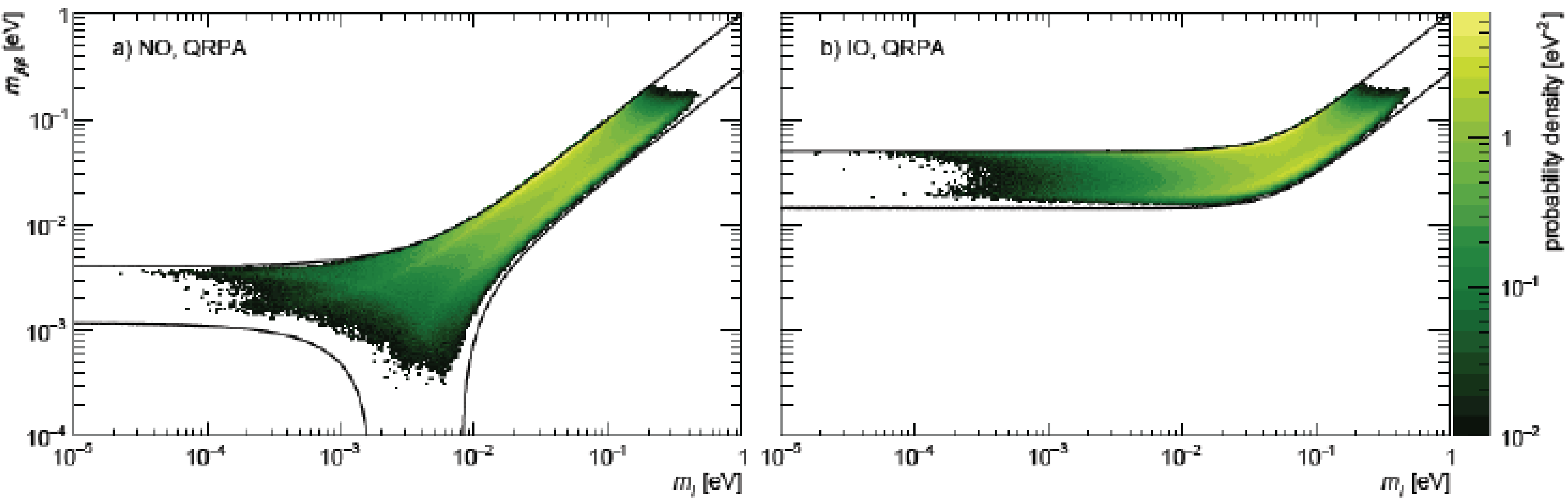
Discovery probability of next-generation neutrinoless double-β decay experiments

Global Bayesan analysis including neutrino oscillations, tritium, double beta decay, cosmology

Ignorance of the scale of the parameters → **Scale-invariant prior distributions**

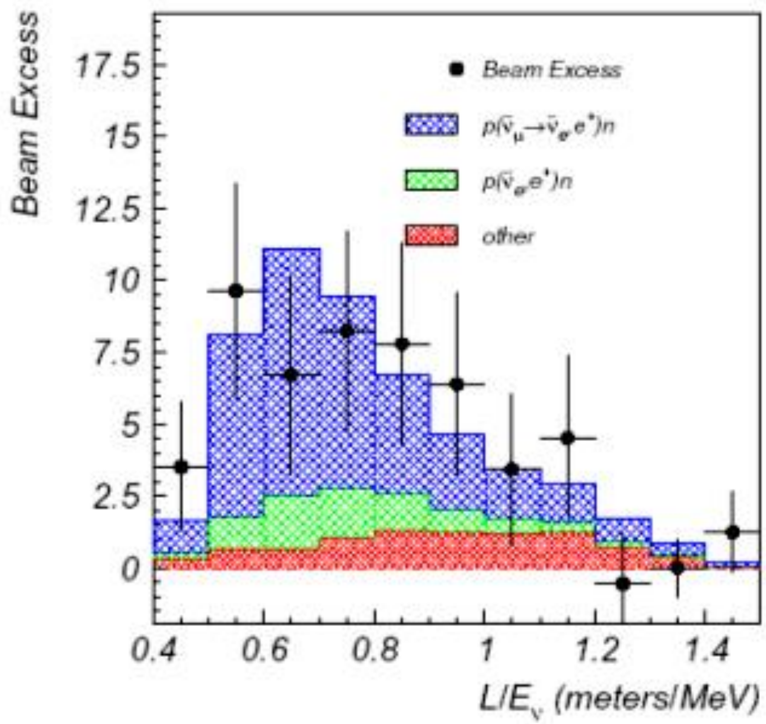
- $\Sigma = M_1+M_2+M_3$, ΔM_{ij}^2: **logarithmic**
- Angles and phases: **flat**

Marginalized posterior distributions of $m_{\beta\beta}$



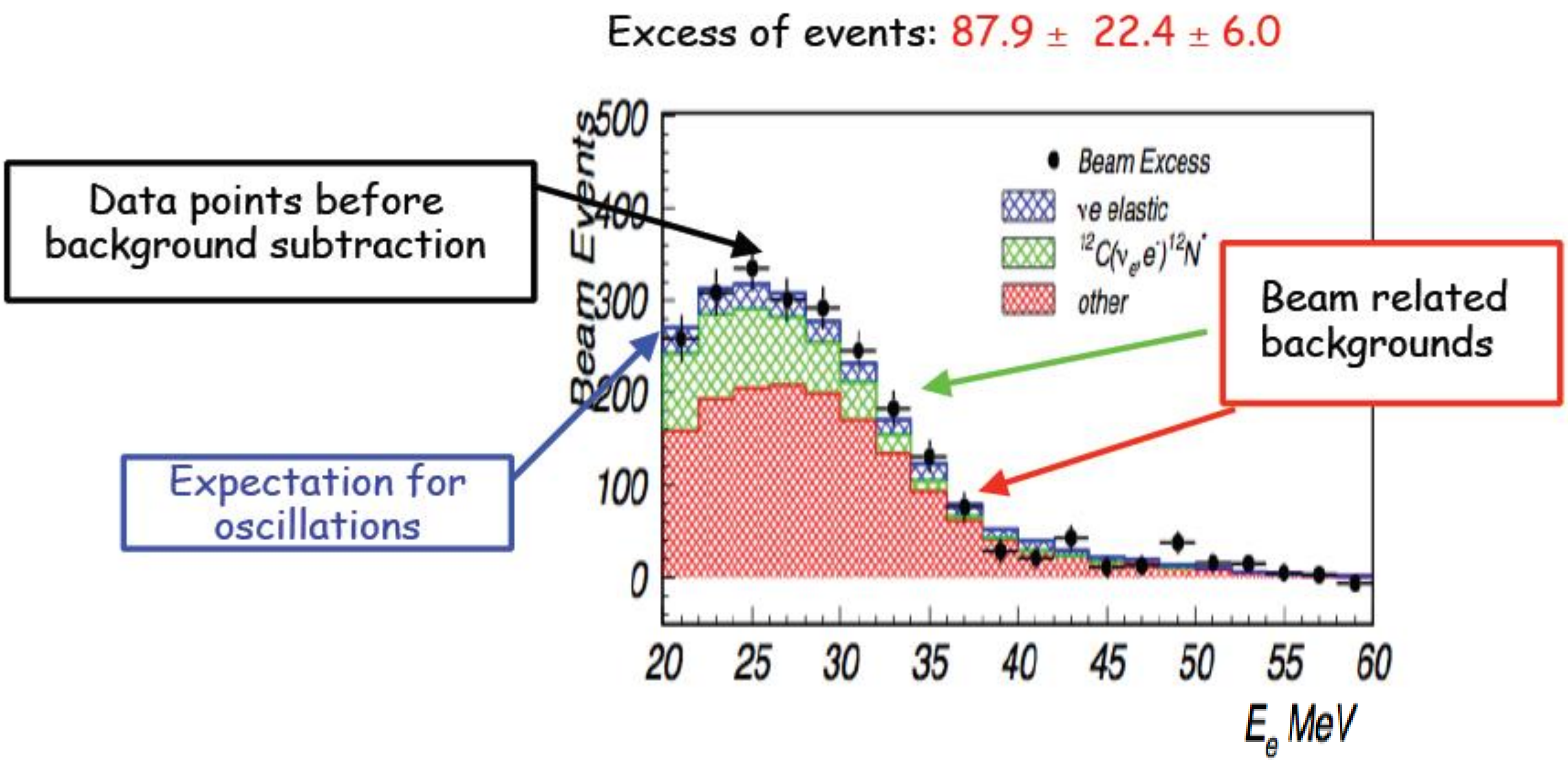
Sterile Neutrinos: LSND Starts it all...

- Backgrounds in green, red
- Fit to oscillation hypothesis in blue

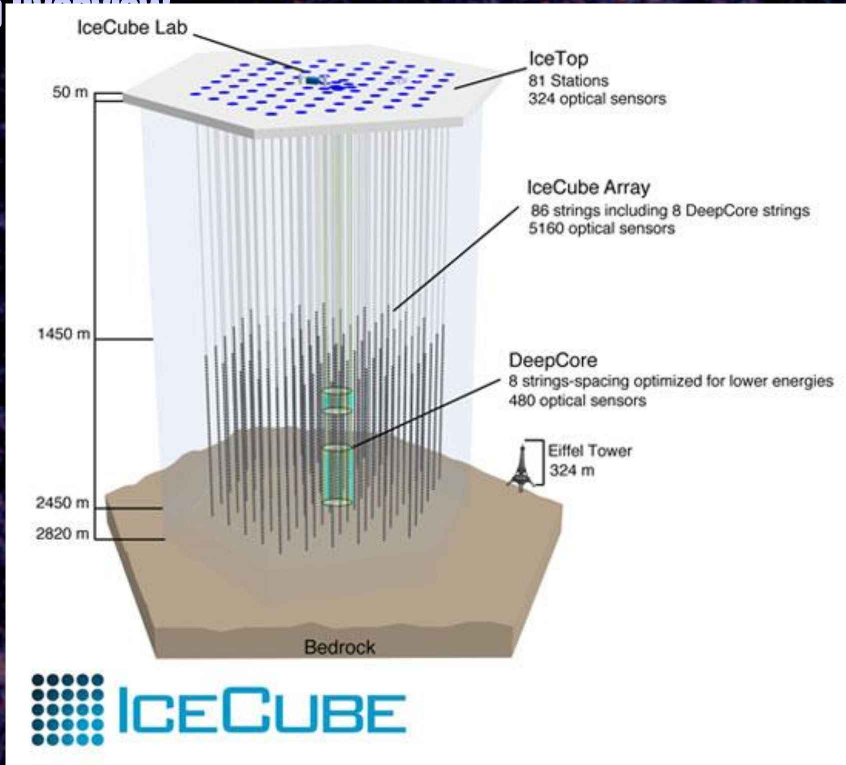


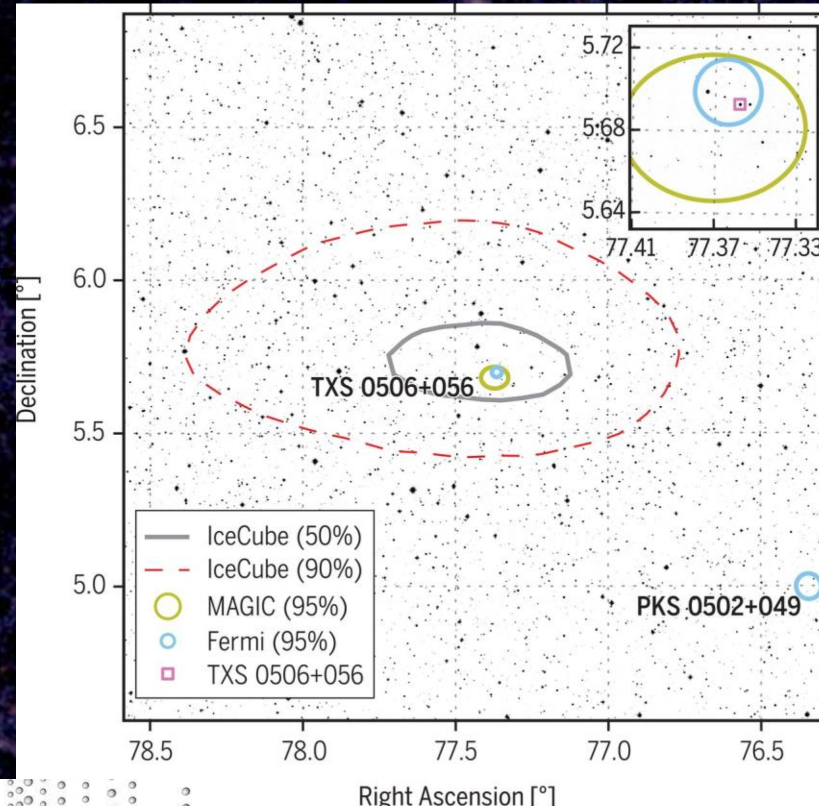
Excess of electron anti-neutrinos in a "beam" from stopped pion decay…

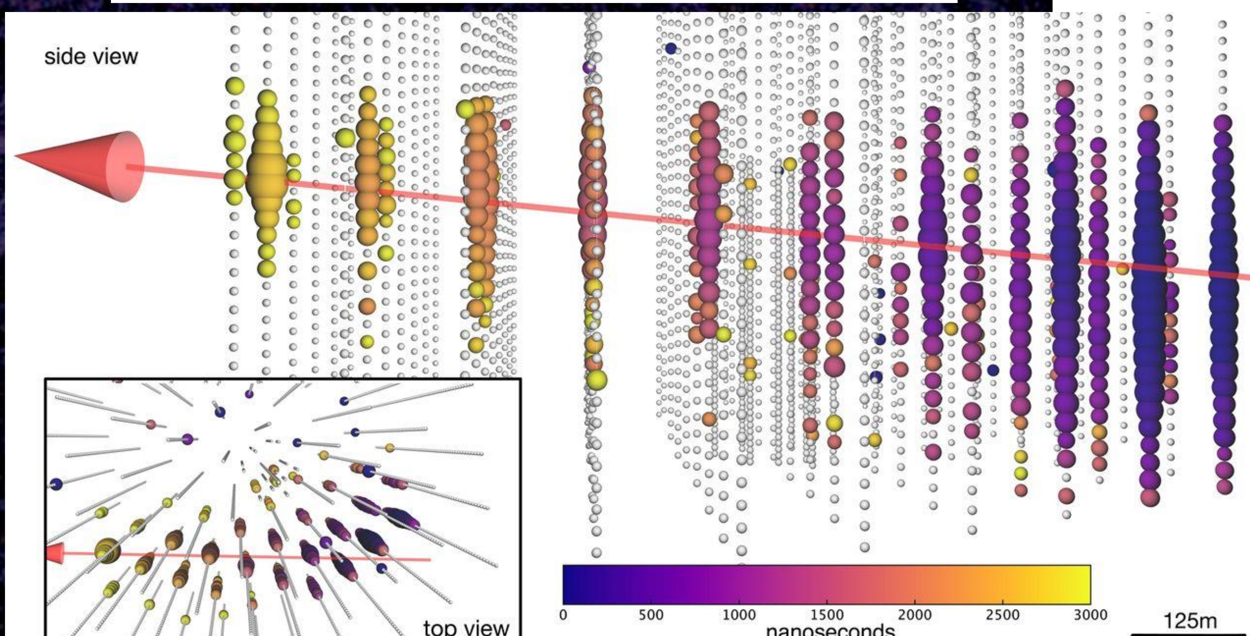
LSND Starts it all...



This is a tiny effect, and systematics will be crucial. It is a pity SBND is first!







Dave Wark
Oxford U./RAL

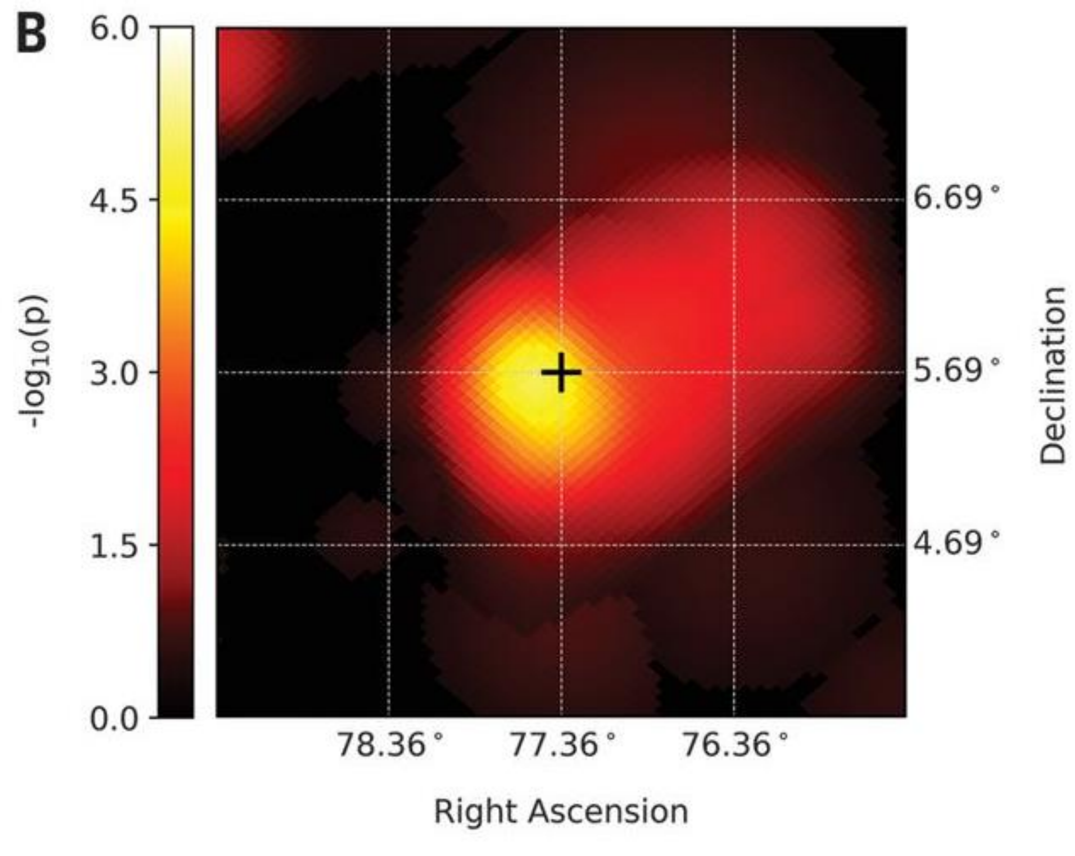
RESEARCH ARTICLE

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

IceCube Collaboration[*,†]

+ See all authors and affiliations

Science 13 Jul 2018:
Vol. 361, Issue 6398, pp. 147-151
DOI: 10.1126/science.aat2890



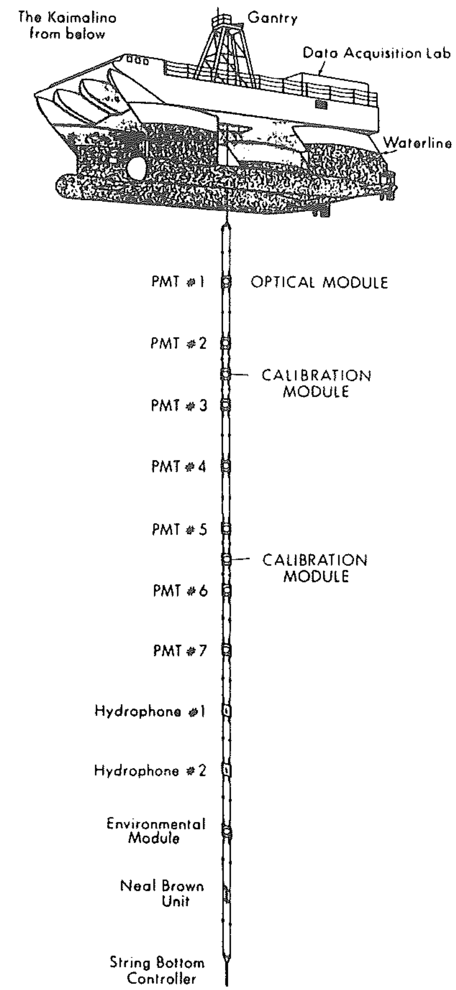
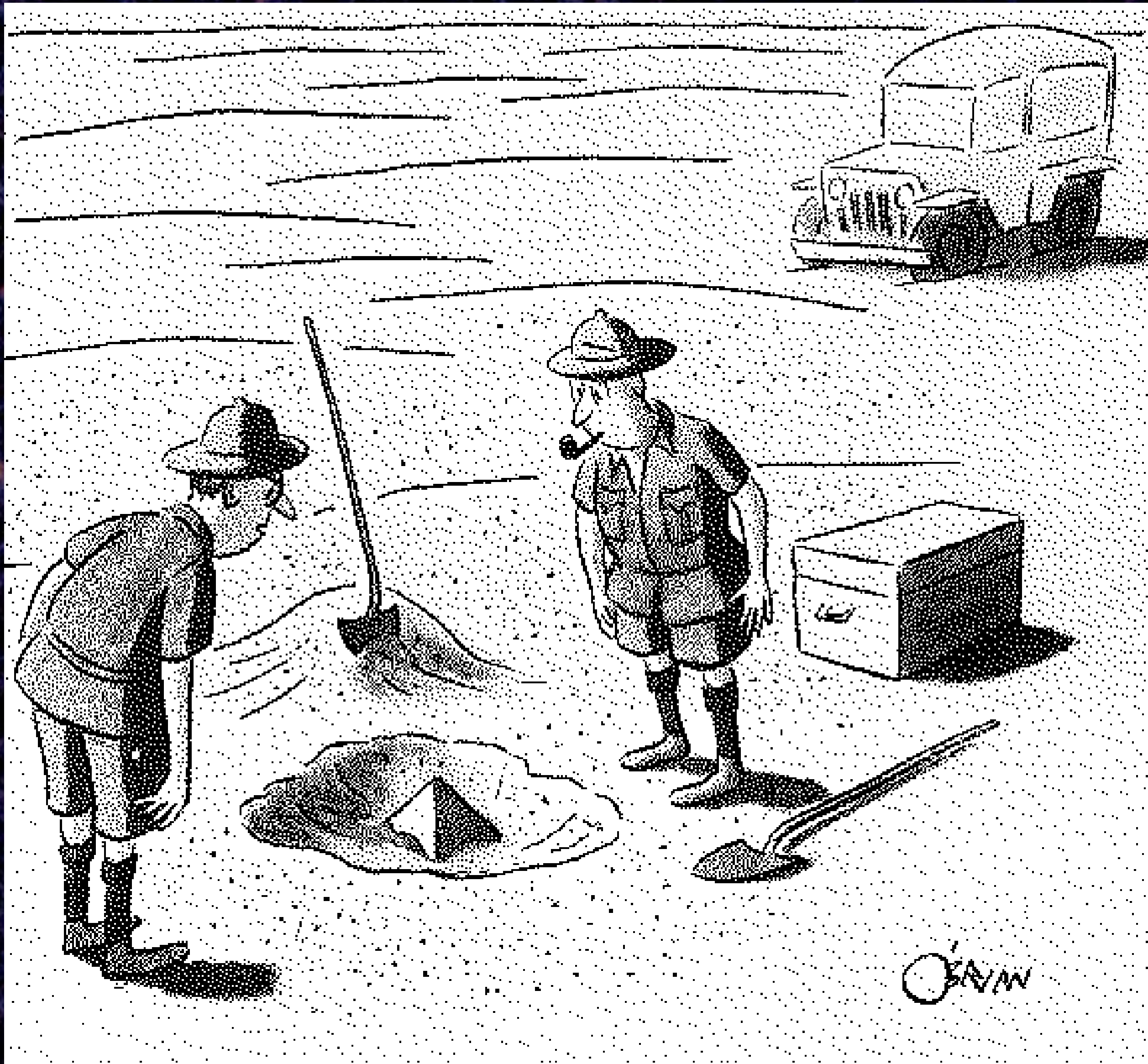


Fig. 1. The DUMAND Short Prototype String. Seven optical modules (PMT) and ancillary equipment are spaced 5.18 m apart along a vertical cable deployed from the center well of the highly stable vessel Kaimalino.

Conclusions

- Neutrino Oscillations have gone from speculative to routine, and remain the only experimentally confirmed particle physics beyond the original Standard Model.
- Every 3ν neutrino mixing (i.e., every angle) has been seen by at least two different methods and by multiple experiments – so we can believe them!
- We have moved from exploration to the era of precision measurements – but that opens a window for new discoveries.
- Nuclear physics matters – this will require supplementary experiments and theoretical support.
- There is much more neutrino physics outside of oscillations – absolute mass, Majorana vs. Dirac, use of neutrinos as probes, astrophysical and cosmological ν, and the search for deviations.
- Somebody must sort out sterile neutrinos (and there are non-accelerator experiments in that area moving as well), but it is a very subtle problem so don't look for very rapid progress.
- This is great physics, and we need more physicists!
- Join us!



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Dave Wark
Oxford U./RAL